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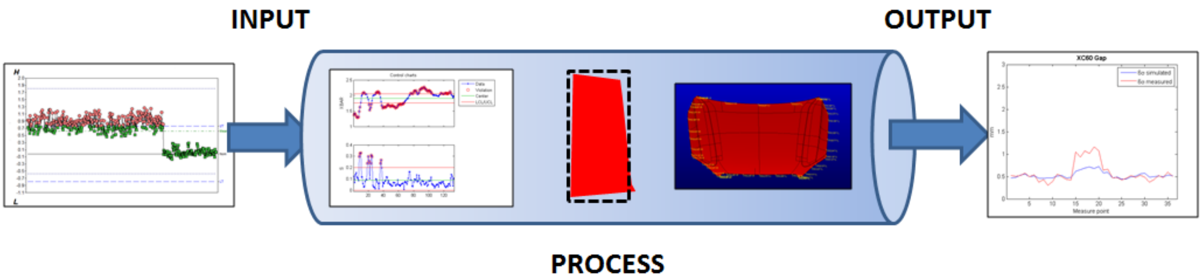

Possibility of Implementing Part Related Tolerances in Variation Simulation

Master's thesis in Product Development

FREDRIK ALPHONCE
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Department of Product and Production Development
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Cover:

Method for investigating the possibility of using part related tolerances. Starting with gathering sample data, then normalize the data, make a best fit and finally perform a simulation in RD&T.

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Abstract

In manufacturing, variation is always present. The department Robust Design and Tolerancing at Volvo Car Corporation works with quantifying the variation and finding suitable locating systems. In order to increase the precision and reduce the need for manual work part related tolerances have been investigated in this project. The work has mainly been done in RD&T and Matlab, and is documented in this report.

By investigating measure data and make a best fit it was possible to remove the effects from positioning variation and only focus on the part variation. The mean of the variation was calculated for several models and components. This resulted in part related tolerances, which were applied in the simulation models. The simulated results were compared with the measure data to identify correlations.

It turned out that some components gave very promising results and some were not as promising. Especially the simulations of gap measures gave aligning plots. Before implementing the function in RD&T more components should be observed.

Keywords: *Part related tolerances, Robust design, Quality management, RD&T, Geometrical variation.*

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Thank you!

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1 Introduction

This chapter explains the background to why this master's thesis was initiated. It also presents the purpose, the goal and the scope of the project.

1.1 Background

When manufacturing products it is not possible to make two that looks exactly the same. There will always be some variation. One way to handle this is to work with robust design, which means that the design is insensitive to variation. This is the most important contributor to improved geometrical quality (Hellström & Soppela 2013). In the luxury segment of the car industry one of the most critical factors is the aesthetics, such as gap and flush relations between surfaces (Hellström & Soppela 2013). These relations are heavily dependent on the robustness and the capability of the processes used to manufacture and assemble the ingoing parts.

At Volvo Car Corporation (VCC) the department called Robust Design and Tolerancing develops designs that are robust and will work even though the components are not nominal. The most commonly used software is called "Robust Design and Tolerancing" (RD&T) and it is used to perform variation, contribution and stability analysis on different parts on the car.

RD&T is constantly developing through thesis work by master- and PhD-students, but also in close cooperation with companies using the tool. This master's thesis was initiated as the engineers working with the tool RD&T at VCC needs faster working methods and more reliable data.

1.2 Purpose

There are different types of variation. One of these is that the shape and other properties of a part always deviates slightly from the nominal design, this is called part variation. Depending on how it is positioned the variation may be amplified differently. This is called positioning variation.

In reality, when a part is in its fixture the observed variation will grow with the distance from the reference point. A reference point, also called locating point, locks a part in one or many directions in order to position the part for assembling or measuring. A fixture is a physical representation of the reference system, which holds the part in place. Close to the reference point it is more likely that the variation is observed as smaller than further away from it. The current version of RD&T supports this when using tolerances in the locating points. The variation is then amplified further away from the reference point. But when working with subsystems, which are often done to reduce the size of the models, it is not always possible to have a tolerance in the locating points. Then the tolerances have to be recalculated and put in manually. This requires a lot of work.

If one wants to study the part variation, several points must be created along the part with individual tolerances growing with the distance from the reference point. When changing the reference system all tolerances must again be changed. This takes a lot of time and is not always done by the robust design engineers at VCC. Instead the same tolerance is set to all points, which is not very accurate, and it does not mirror the actual variation. Figure 1 shows the different concepts. The left figure shows the reality, how the observed variation grows further away from the reference point. The reference point is illustrated with a red triangle. The figure in the middle shows the current working method, which does not replicate the growing variation showed by the left figure. The figure to the right illustrates that the tolerances are adjusted to the current reference system and grow further away from the reference point. This would be a better working method, as it would simulate the variation more realistically.

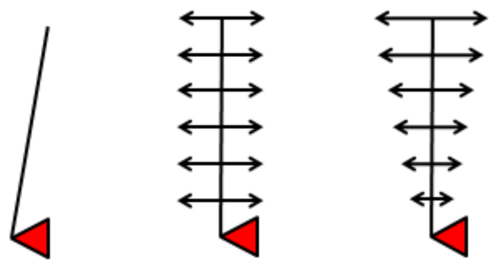

Figure 1 - Different concepts of amplifying tolerances

The robust design engineers have to make qualified guesses on the size of the tolerances. When developing a robust system the work with finding a suitable reference system is iterated to find a satisfactory solution. The robust design engineers at VCC believes that it would be desirable to have the part variation automatically given by the software with respect to the given reference system and the type of component. This would provide them with a faster working method and more accurate results from the calculations done in RD&T.

The purpose of this master's thesis was to investigate the possibility to use part related tolerances in RD&T based on previous knowledge of manufacturing. Part related tolerances means that a specific value can be set on all tolerances for one type of component. Different components will have different part related tolerances. But also different type of measures could have different part related tolerances.

1.3 Goal

The main question of this project is: "Is it possible to use part related tolerances?" The goal of this master's thesis is to answer the question by determining if it is possible to identify a correlation between measured and simulated data. If there is a correlation, steps towards an implementation of part related tolerances in RD&T could be taken.

The goal is also to deliver advice on how to proceed with the knowledge gained from this master's thesis along with a demonstration of how the new function could work in RD&T - if part related tolerances could be used.

1.4 Scope

The project started on the 19th of January 2015 and continued for 20 weeks. The Gantt-schedule for this project can be seen in Appendix 1. The Gantt-schedule shows the time spent on different tasks and when the tasks were carried out. The students put in the same amount of effort and time into the project and the workload was equally shared.

The project was a master's thesis at Chalmers University of Technology and made in accordance to the regulations.

The scope of the project was to investigate the possibilities of identifying and implementing part related tolerances in the software RD&T. This was done by looking at four components on several cars: the left front door, the left rear door, the left rear lamp and the bonnet. Only rigid simulations were made because compliant simulations were considered too time consuming for the purpose of this project.

A finished and implemented function in RD&T was not intended to be delivered, but rather the pre work to determine if part related tolerances is possible or not. The conclusion might very well be a statement that part related tolerances could not be identified.

2 Theory

The intention of this chapter is to explain relevant theory, in order to give the reader a better understanding about the subjects addressed in this master's thesis. First quality is explained and why it is of importance for businesses. Furthermore it discusses how to control processes and later what the software RD&T is and how it is used.

2.1 Quality

Quality has always been important for customers when purchasing products or services. Organizations focusing on an innovative and systematic way of working with quality and quality improvement have often achieved great success on the market. Working with quality improvement can also secure lower internal costs and a shorter design and development phase of new products. (Bergman & Klefsjö 2010)

The quality movement has its origins from the "Japanese wonder". This was the reestablishing of the Japanese industry after the Second World War. During this period senior managers at Japanese companies gave quality and its issues a strong focus. The senior managers realized that costs of quality defects, related to changes, scrapings, revisions and delays were significant. By systematically focusing on the customers' needs and working with quality improvement and waste reduction Japanese companies managed to claim and dominate several areas in the international market in the 1970s and 1980s. One example is the car industry, where General Motors, Chrysler and Ford, also known as "the big three", were almost obliterated from the car market by Toyota. (Bergman & Klefsjö 2010)

Quality is a perceptual, conditional, and somewhat subjective attribute and may be understood differently by different people. Quality in business, engineering and manufacturing has the definition as the inferiority or superiority of something. Consumers might compare the quality of a product to its competitors and the producer might measure the quality to what degree the product was manufactured correctly (Bergman & Klefsjö 2010). However, there are many definitions of the word quality and new ones are constantly developing. Crosby defined quality as "conformance to requirements" (Crosby 1979), but this is believed by many as being too narrow. The definition is from a producer's point of view and aims to describe the fulfillment of requirements. Joseph Juran expressed quality as "fitness for use" (Juran 1951). Edwards Deming was on the same path but went one step further and said that "quality should be aimed at the needs of the customers, present and future" (Deming 1986). All in all there are two sides of quality: one measurable and one more subjective, dealing with how customers experience the product. Bergman and Klefsjö express that many definitions lack the aspect of exceeding the customers' expectations, the aspect that creates loyal customers and therefore goes on and defines quality as "The quality of a product is its ability to satisfy, and preferably exceed, the needs and expectations of the customers" (Bergman & Klefsjö 2010). Often companies create their own definition of quality in order to have a unique approach to it. A CEO of a small Swedish company expressed that "Quality is when the customer comes back - not the product" (Bergman & Klefsjö 2010).

To maintain and improve quality is often symbolized by the PDSA cycle. Figure 2 illustrates this. PDSA stands for Plan - Do - Study - Act. When a process is found to be in need of improvement, delivering products that vary too much, the PDSA cycle is commonly used. The different aspects of the PDSA can be described as:

Plan: First the problem has to be mapped and the causes for it. Large problems often have to be broken down into smaller ones for it to be manageable. There are different tools used to map the problems such as causes-and-effect diagrams, FMEA or design-of-experiments. When the data has been gathered the time to sort it is at hand. Tools for presenting statistical data is then used such as histograms, scatter plots or Pareto diagrams.

Do: When the root of a problem has been found a task team is assigned to solve it. The task team has to go through appropriate steps mapped in the planning phase to be able to remove the causes. Great importance lies in that everyone involved is fully aware of the problem and the steps to improve it.

Study: Once the task team has implemented the improvement program, the results of it have to be analyzed, in order to determine if it was successful or not. Again improvement tools are used to interpret the statistical data, preferably the same ones used in the Plan process. It is then easy to evaluate the improvement program.

Act: To avoid the same problems happening again it is important to learn from previous mistakes. If the improvement program was successful it should be implemented as the new standard to maintain the quality that has been achieved. If the program was not successful then the cycle has to be gone through again. (Bergman & Klefsjö 2010)

Eriksson continued on this note but stressed the fact that quality improvement only can be increased if it is controlled and maintained by working methods. Meaning that it is not enough to just implement new working method but there should also be ways to control the method. Eriksson implemented two new aspects to the PDSA cycle. First, the quality improvement should be viewed as an uphill. Second, a wedge, quality assurance, supports the cycle. Quality assurance is a structured way to keep control of a process, very much needed to be able to achieve products that meet the desired specifications and helps to further improve the process. (Eriksson 2014)

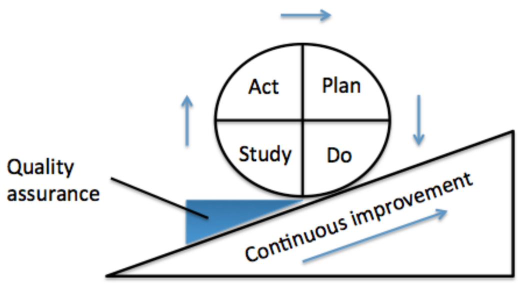

Figure 2 - The PDSA cycle

2.2 Variation

"In all situations of life we experience variations, whose causes we are often unable to identify" (Bergman & Klefsjö 2010). Variation is sometimes good as a world with identical people would be somewhat tiring. However, variation is often inconvenient and a driver for cost when discussing quality. Causes of variation in manufacturing can be vibrations, varying lightning, inhomogeneous materials and varying temperatures or humidity. Causes of variation that can be identified such as tool wear, maladjusted machines or defect in the materials are called "assignable causes". These are causes that can be identified and eliminated. Other common causes that contribute to the variation are called "random causes". Each of the causes may be insignificant but together they are significant. (Bergman & Klefsjö 2010)

In this project two types of variation were studied: part variation, which is due to deviations in the geometry of the part, and positioning variation, which comes from deviations in the positioning of the parts.

2.3 Standard deviation

Standard deviation, represented by the Greek letter σ, is a measure of how a set of data varies from the mean, see Figure 3. The more spread out the data is from the mean the more the deviation will increase. If the data is close to the mean the standard deviation will be low. 6σ is equal to 99.8 % of the distribution. Standard deviation is calculated as the square root of its variance. If the standard deviation is close to 0 it indicates a small distribution and the values are close to the mean of the set. A high value indicates a large spread of the data. Variance is another measure of how far a set of data is spread out, namely the square of the standard deviation. The variance and the standard deviation are always positive (Weisstein 2015).

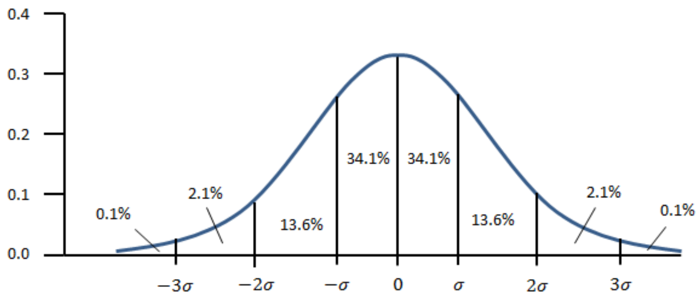

Figure 3 - Normal distribution

When manufacturing products one wants these to vary as little as possible from the nominal design, in other words the standard deviation should be low. By removing causes that are assignable the process can be considered to be under statistical control, the process is stable. When the assignable causes have been discarded the random causes are the only things left that affect the process. It is useful to have a stable process as the future can then be predicted. It is then possible to identify new assignable causes and eliminate them from the process or compensating for them. (Bergman & Klefsjö 2010)

2.4 Null hypothesis and p-value

The p-value is used to determine the significance of a hypothesis test. In samples coming from for example measuring there is a difference between the groups that the operator wants to determine. It could be the effectiveness of a new fixture that is being tested. There is however a chance that there is no difference from sample to sample. This lack of difference is called the “null hypothesis”.

Imagine the experiment of a drug that from the start is known to be 100 % ineffective. Then the null hypothesis would be true: There is no difference from sample group to sample group at the population level. The p-value evaluates the likeliness for the null hypothesis to be true. It measures how well a set of data is compatible with the null hypothesis. High p-values indicate that the data is true to the null hypothesis and low p-values states that it is untrue. A low p-value states that the null hypothesis can be rejected for the entire population. The p-value is the probability to obtain new data that is at least as extreme as the one already in the sample, assuming that the null hypothesis is true. A p-value of 0.95 or above indicates that the process is normally distributed and can be viewed as such. (Frost 2014)

For example, assume that the measuring of several bonnets gives a p-value of 0.97. This value says that there is a 3 % likeliness that the next bonnet being measured will not correlate with the previously measured bonnets. It can be a gap measure that does not fall within the sample range but rather outside of it. This particular process can be viewed as stable, normally distributed and it is predictable. High p-values are commonly desired for a process.

2.5 Control charts

The use of control charts is common to supervise a process. With the help of control charts one can quickly identify assignable causes. By gathering data from the process, such as measuring a component at a given interval, information can be found of how the product varies from the nominal. The measured data is used to calculate a process quality indicator and is then plotted in a diagram (Bergman & Klefsjö 2010). Bergman and Klefsjö explain this as “A process quality indicator is an observable quantity based on the observations indicating the status of the process characteristic of interest” (Bergman & Klefsjö 2010). Manufacturing processes are often supervised by using several process quality indicators. If the plotted quality indicator remains within its limits it is said that the process is stable. The limits are called control limits and between these control limits is a central line that describes the mean of the output.

Control limits and tolerance limits are completely different things. The control limits are used to describe how stable a process is. The tolerance limits are used to evaluate if a single product fulfills its set requirements. The control limits are the voice of the process and the tolerance limits are the voice of the customer. 3σ limits are commonly used as control limits. Figure 4 shows a typical control chart.

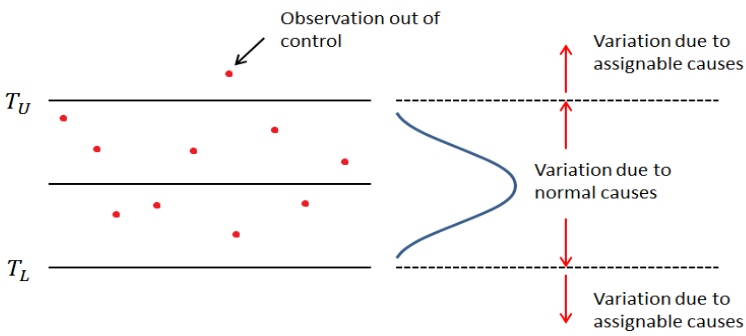

Figure 4 - A typical control chart

The basic intention of a control chart is to quickly indicate when a change has occurred in the process, as a result of an assignable cause. The control chart should contribute to its identification. It should also be easily interpreted and easy to use. It must indicate if the process is stable, i.e. in statistical control. False alarms must be rarely occurring. A false alarm is when a plotted point is outside the control limits when no assignable cause has occurred. It should work as a receipt, proving that improvement work has been successful. It should also work as a basis for evaluation of the process capability. (Bergman & Klefsjö 2010)

2.6 Capability

The ability of a process to produce units within the defined dimensions or tolerance limits is called capability. Using the information from the control charts one can define several measures of the capability of a process. In order to use these capability measures the process that is investigated have to be stable. The capability is based on the expected mean of the process μ, and the standard deviation σ together with the upper and lower tolerance limits (Bergman & Klefsjö 2010).

The capability index is widely used to measure the ability for a process to produce within defined tolerance limits. The capability index is defined as:

$$C_p = \frac{T_u - T_l}{6\sigma}$$

Where T_u is the upper tolernance limit, T_l is the lower tolerance limit and σ is the standard deviation.

Bergman and Klefsjö explain the capability index measure as: "The index states how large a part of the natural variation of the process, a common name for 6σ, is occupied by the tolerance interval" (Bergman & Klefsjö 2010). A large value on the capability index indicates that the dispersion of the produced units is small, and a small value indicates a large dispersion. One downside with the capability index is that it does not take into account where the center of the process is, only the dispersion. The capability index and what it indicates is explained in Figure 5.

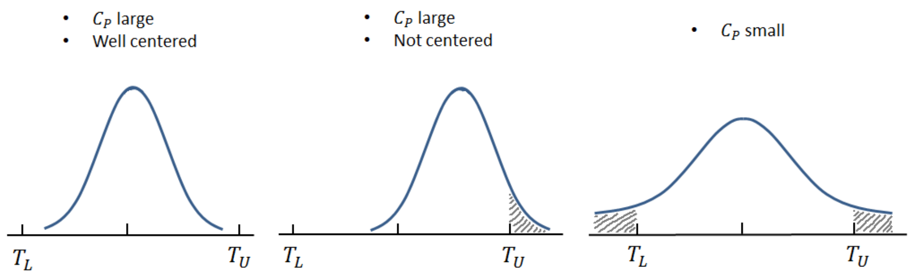

Figure 5 - Illustration of capability index

The adjusted capability index takes both the dispersion and the centering of the process into account, in other words how well the process mean correlates with the target value. The adjusted capability index is defined as:

$$C_{pk} = \left(\left(\frac{T_u - \mu}{3\sigma}\right), \left(\frac{\mu - T_l}{3\sigma}\right)\right)$$

Where T_u is the upper tolerance limit, μ is the mean, T_l is the lower tolerance limit and σ is the standard deviation.

The index measures the distance between the centering and the closest tolerance limit (Bergman & Klefsjö 2010). Figure 6 explains the relationship between the capability index and the adjusted capability index.

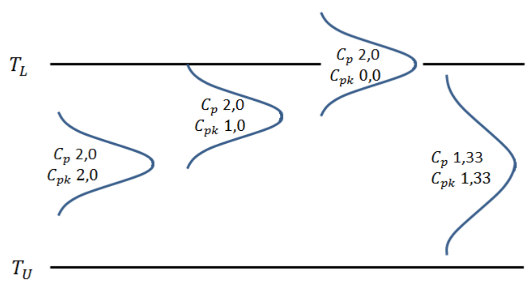

Figure 6 - Relation between capability index and adjusted capability index

2.7 Moving average

The average value of the process will vary with time. This is influenced by various shifts, different machines or varying material properties. The variation can then be viewed in the average value of the process as a random variable, whose deviation is possible to estimate. There are two components to this dispersion: variation in unit to unit and a deviation that is affected by usually slower variation of the average value. The first mentioned variation is subject to machine capability and process capability takes both dispersions into account. This breakdown of the capability notion is strongly associated with manufacturing processes (Bergman & Klefsjö 2010). A very clear mean shift is illustrated in Figure 7. That is the result of an assignable cause suddenly being eliminated.

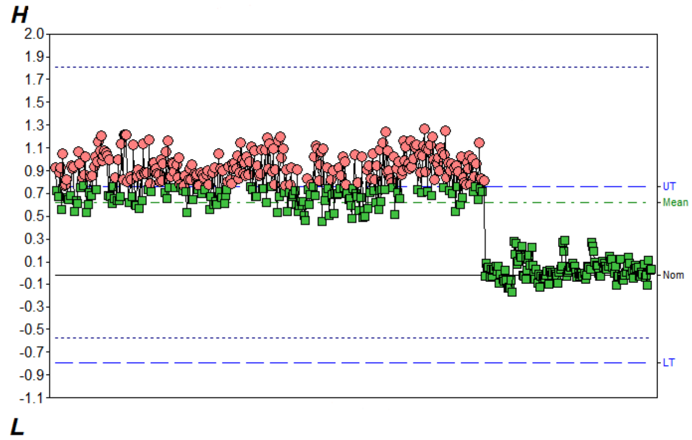

Figure 7 – A mean shift

To be able to estimate the process capability, the process needs to be studied over a long period of time. This estimation cannot be based in a normal control chart, as the process mean will inevitably change. Machine capability can be calculated using s_j and j=1,2...k, where k is the number of samples taken from the process. s_j is the standard deviation in each sample respectively. (The mean of the process is not considered here because only the deviation is relevant in this project.)

$$s_w = \sqrt{\frac{1}{k}\sum_{j=1}^{k} s_j^2}$$

s_w is an estimation of the dispersion σ_w in the same sample. The variation from the process can be explained by two components. σ_w, the dispersion within the sample, and σ_b, which is the dispersion between samples. The total dispersion can be explained as:

$$\sigma = \sqrt{\sigma_w^2 + \sigma_B^2}$$

(Bergman & Klefsjö 2010)

2.8 Tolerances

When assembling a product the tightness or clearance between the joining parts are important. The tolerance is the allowable variation to achieve the wanted function (Lilja et al. 2009).

If the holes and pins are given the same dimension as depicted in Figure 8, the tolerances of them are H7 or h7 respectively and the positioning tolerance is 0.1 mm the blocks have a probability of 0.1 % to fit together. A way to counter this is to specify the holes a little bit larger than the pins, in that way the parts will always be able to assemble. The holes and pins will then be assigned their tolerances that will always allow the parts to be assembled. (Lindkvist 2013)

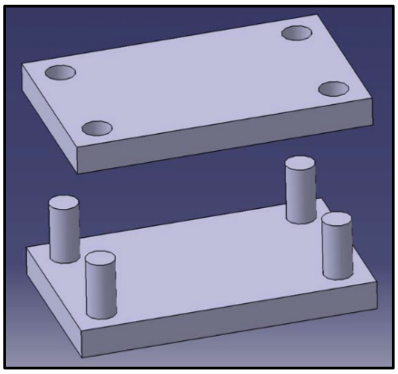

Figure 8 - Holes and pins of the same size (Lindkvist 2013)

When making the holes a little bit larger than the pins, the assembled part will be loose. This is often not satisfactory for a product and to make the assembled parts fix, one can work with the dimensioning of each hole. In Figure 9 this is solved by making one hole a little bit tighter and one hole elongated with a width slightly longer than the diameter of the pin, which will lock its movements in all degrees of freedom (Lindkvist 2013).

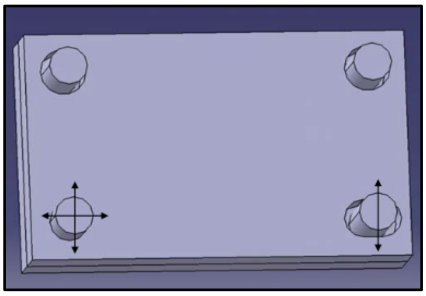

Figure 9 - Hole, slot and oversized holes (Lindkvist 2013)

Specifying tolerances in this way will make the design insensitive to variation, the design will be robust. A primary concern when setting tolerances is to determine the width without it affecting other factors. Often experimental investigations are used in order to determine the effects of tolerances. This is often done using design-of-experiments (Lilja et al. 2009).

Tolerances are set on parts for manufacturing purposes, limits for acceptance build. As no machine can hold dimensions precisely to the nominal value, there must be acceptable degrees of variation. The commonly used terms for setting tolerances are:

Basic size: The nominal geometry of the part.

Lower deviation: The difference between the lowest allowed component size and the basic size.

Upper deviation: The difference between the maximum allowed component size and the basic size.

Fundamental deviation: The minimum difference between a component and the basic size. If the fundamental deviation is greater than zero, the pin will always be smaller than the basic size and the hole will always be wider. Fundamental deviation is more of an allowance rather than a tolerance.

To communicate the specified tolerances Geometric Dimensioning and Tolerancing (GD&T) is used. GD&T is a symbolic language on engineering drawings that describes the nominal geometry and the allowed variation. GD&T communicates to manufacturing what kind of precision is needed on each part. The dimensioning describes the nominal geometry, the theoretically perfect geometry. Tolerancing describes how the geometry may vary and still be able to achieve its intended purpose (Lilja et al. 2009).

The philosophy of GD&T is to describe the geometric requirements for part and assembly geometry. Proper use of GD&T ensures that all parts within its tolerances will be able to be assembled with its intended properties fulfilled. To be able to achieve this, certain fundamental rules should be used. All dimensions must have a tolerance. As every manufactured part is subjected to variation, therefore limits for allowed variation must be specified. All tolerances and dimensions are only valid in its free state, unless explicitly stated. Description of manufacturing method should be avoided, but should work as a guideline for what to use. Dimensions and tolerances only apply at the level of the drawing where they are specified. It is not mandatory that they apply at other drawing levels. Dimensions and tolerances apply to the full length, width, and depth of a feature including form variation. (Lilja et al. 2009).

2.9 Taguchi's loss function

The traditional view of tolerances is that everything within the limits is approved and there is no loss of function. Genichi Taguchi, one of the pioneers within quality improvement, presented a loss function that is quadratic, see Figure 10. In the nominal case there is no loss of function. But the more it deviates from the nominal design the worse it gets (Bergman & Klefsjö 2010). However, in reality it may not be a perfect quadratic function. For example, in the case of a car door the function will be lost entirely when there is a clash between the door and the car body (Johansson 2015). But within reasonable limits Taguchi's view is more similar to the reality.

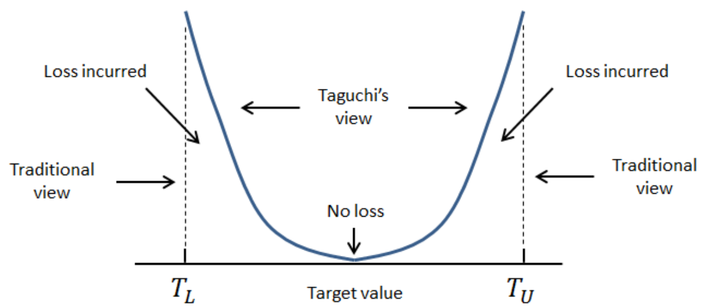

Figure 10 - Taguchi's loss function compared to the traditional view

This theory presents how the variation can be viewed. The tolerances can still be used as limits of what to scrap and what to keep. The further away from the nominal design the product is, the more loss of function it will have. All parts within the limits do not fulfill the requirements equally well. Therefore Taguchi's view of variation is better to use when developing products (Bergman & Klefsjö 2010).

2.10 Robust design

Small tolerances are closely coupled with high costs. To minimize this problem it is possible to work with robust design, which makes the design insensitive to variation. Robust design is a systematic method aiming at predicting component variation before it occurs and then minimize it through the design (Silverstein et al. 2009). Söderberg and Lindkvist define it as “A geometrically robust design is a design that fulfills its functional requirements and meets its constraints even when the geometry is afflicted with small manufacturing or operational variation.” (Söderberg & Lindkvist 1999). It is often more expensive to control the causes of variation than to make the process insensitive to variation (Bergman & Klefsjö 2010). Discarding robust design may result in products with lower quality and higher manufacturing costs. “Selecting a less robust component from a supplier with a lower sales price could however generate a higher total cost if it is more expensive to produce and maintain in the aftermarket.” (Hellström & Soppela 2013). Tight tolerances are associated with high costs, thus the allocation of tolerances must be done with respect to the current situation (Söderberg et al. 2006).

Robust design can be explained with the parameter diagram, see Figure 11. The parameter diagram illustrates how different inputs affect the output of a system. The signal factors (M) are ideally affecting the output. A signal factor can be illustrated as the user turning the steering wheel of a car. Ideally the deviation around the nominal response curve (y) should be small even when influenced by noise factors (N). Noises are factors that disturb the process, things that the engineer does not have control of. This can be explained as the user wants to turn the car but the wheels are affected by state of the road. The control factors (Z) are typically elements such as design, materials and processes that the engineer has 'control' over (The_Quality_Portal 2007) (Bergman & Klefsjö 2010). Together these inputs form the output of the system and can be described as y = f(M,Z,N). A robust design is insensitive to the noise factors.

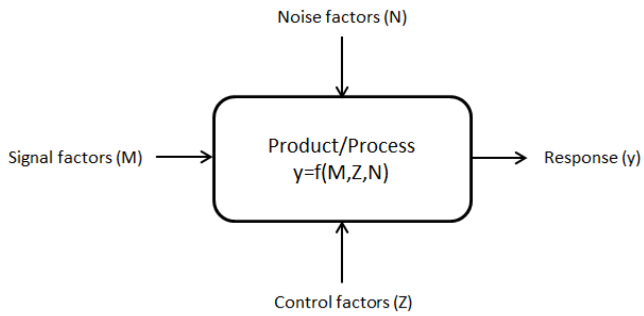

Figure 11 - Parameter diagram of robust design

To consider robust design early in a product development effort is important to develop designs that will fulfill the required properties. Söderberg et al. describe it as “the means of managing variation and secure function, form and assembly, is by assigning tolerances that restrict the permitted variation of a geometrical feature” (Söderberg et al. 2006). Working with robust design one can avoid discovering designs late in the development process that are sensitive to manufacturing variation and that needs to be redesigned. Redesign in a late stage of the development process is an expensive matter and is preferably avoided. In the concept phase the product and the production units are analyzed and optimized to withstand the effect of manufacturing variation and tested virtually against production data (Söderberg et al. 2006).

Later in the verification and pre-production phase the product and the production system is physically tested in order to verify it. In the production phase all the production adjustments are finished and focus now lies on controlling the process and to detect and correct errors. The knowledge gained in the production is later used as input for new concepts, see Figure 12 (Söderberg et al. 2006).

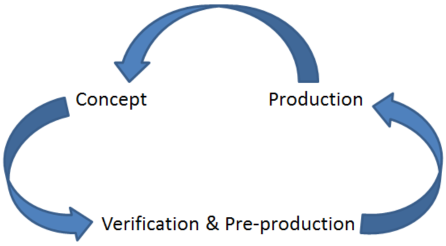

Figure 12 - The geometry assurance process

2.11 Locating schemes

The purpose of a locating scheme is to lock the position of a part in space. The most common locating scheme is the 3-2-1 and is used for rigid parts, see Figure 13. The purpose is to lock a part's six degrees of freedom in space using six points, also called reference points. The three primary points: A1, A2 and A3 defines a plane and controls (in this case) the translation in Z and rotation around X and Y. The points B1 and B2 control translation in Y and rotation around Z. The last point, C1, controls the translation in X (Söderberg et al. 2006). These six points define the position of the part throughout the whole process. In some phases it might be easier to hold the part in other points, but the locating points are still used as reference. When positioning a non-rigid part more than six points are used to secure the position. The additional points are called support points (Lindkvist 2013).

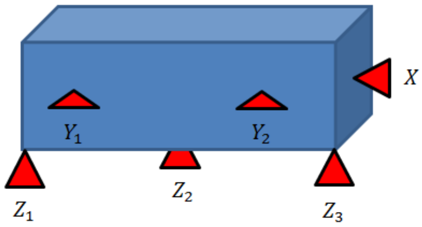

Figure 13 - The 3-2-1 locating scheme

The choice of locating scheme will affect how the variation is perceived, as seen in Figure 14 below. This is called positioning variation. Figure 14 shows a manufactured part, the blue rectangle, with its inevitable deviation from the nominal design, which is illustrated with the dotted lines. The part is positioned with 3-2-1, where the points that define the plane is not visible due to that the part is observed from above and the part rests on the plane that these points define. The variation is amplified by the positioning system. A robust system makes the amplification of the positioning variation smaller than a non-robust system. In other words the variation is perceived smaller with a more robust system. A non-robust positioning system will amplify the variation, making the variation look larger than it is (Johansson 2015). It is important to keep in mind that the part variation is always present and it is important to try to minimize the effects of it.

In Figure 14, the left reference system is more robust than the right one since it is less sensitive to variation. In the right one variation is amplified and the positioning is less satisfactory. Generally it is better to have the reference points as far away from each other as possible, making the area in between them as large as possible.

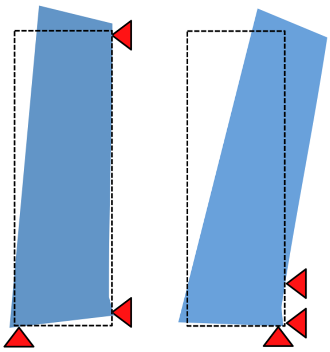

Figure 14 - Left: Robust system, Right: Non-robust system

A fixture physically represents the positioning system, see Figure 15. The purpose of a fixture is to lock a parts position in space in the same way for every part that it handles. The main functions of the fixture is that it should be repeatable and accurate, meaning that the process of positioning should be able to be done several times and the positioning should be the same for every part (Lindkvist 2013). Fixtures can be used when manufacturing a part, for example milling a shape from raw material. The raw material needs to be positioned in a way that allows the tools to work but also to hold the object in space. Fixtures are also used when assembling parts, for example assembling the bonnet to the body of the car. Then the bonnet and the body are positioned in a way that the parts are always at the same place for every assembly. The parts are then joined together. If the fixtures are non-robust and amplifies the variation, the bonnet would be assembled to the body creating split lines that probably would not fulfill the requirements from perceived quality (Johansson 2015). In Figure 15 the front fender for a Volvo XC90 is positioned with a fixture for measuring. As the front fender is non-rigid and deforms easily it needs to be positioned with more points than the reference points in the 3-2-1 locating scheme. These support points help the reference points to achieve the intended shape of the part.

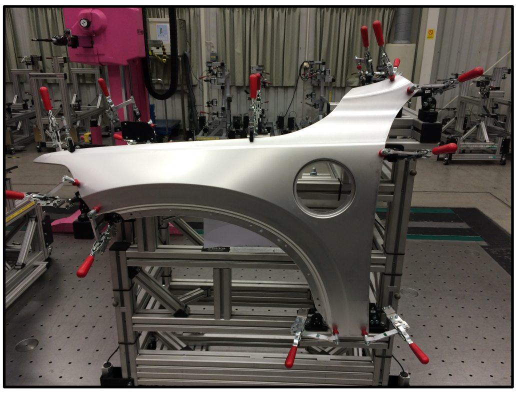

Figure 15 - Fixture for the front fender of the Volvo XC90

2.12 Best fit

Ideally the part should be positioned in a way that the variation from the positioning would be as small as possible. Positioning of a part with its deviation as close as possible to the nominal is called a best fit and is illustrated in Figure 16. Best fit strives to achieve the same variation everywhere on the part with respect to the nominal design. Positioning a part according to best fit is unfortunately not realistic as it would violate the rule of fixtures that states that it should be repeatable. To achieve a best fit physically of the part, the fixture would have to be adjusted for every single component.

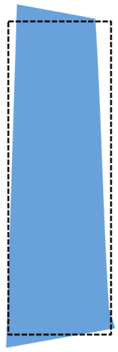

Figure 16 - A part positioned with best fit to the nominal design

A best fit could be achieved by calculating the least square value of the deviation in every point. The least square value should preferably be equal in all points to achieve a satisfactory best fit. The least square value is especially useful when comparing both positive and negative numbers, which is the case when making a best fit. Some points are outside and some are inside the nominal design. Usually it is not possible to have equal value in all points since the part might not be perfectly scaled. It is then necessary to strive for as equal values as possible. (Johansson 2015)

Positioning with best fit might not be good when simulating for example an assembling process. But when looking only on the part variation and not taking into account the positioning variation it is useful. In this master's thesis it was used because only the part variation was studied.

2.13 Gap, flush and parallelism

The relation between two surfaces can be of three types. Gap is the distance between two surfaces as seen in Figure 17. Flush is the distance in normal direction between two surfaces, as seen in Figure 18. The parallelism between two surfaces is how the distance varies along the split line, which can be seen in Figure 19. (Lindkvist 2013) In this project gap and flush have been the main focus.

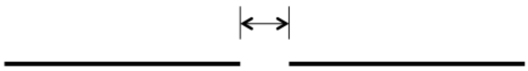

Figure 17 - A gap between surfaces

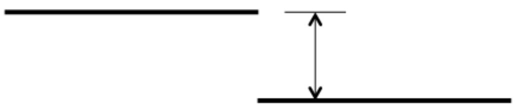

Figure 18 - A flush between surfaces

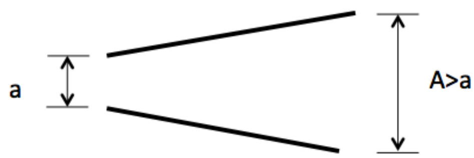

Figure 19 - Parallelism between surfaces

2.14 RD&T

The department of Robust Design and Tolerancing at VCC works with creating robust systems in order to manufacture and assemble parts that have the expected properties. The robust design engineers mainly work with the software RD&T.

"RD&T is a tool for statistical variation simulation that allows manufacturing and assembly deformations of the product to be simulated and visualized long before any physical prototypes are being made." (RD&T_Technology 2015). The tool is primarily used for assembly simulations focusing on geometric stability, sensitivity and variation analysis of complex products, taking into account both product and tooling design (Lindau et al. 2013). The software allows simulation of variation, contribution and stability. Monte Carlo-simulation is used, meaning that numbers are randomly generated for the different inputs within the tolerances and these generate variation of the output as the procedure is repeated (Söderberg et al. 2006).

With the stability analysis it is possible to color code the model to see what areas are sensitive to variation. This is useful to know when designing the locating scheme and the information is beneficial to have early in the process to be able to make the design as robust as possible.

2.15 Measuring

To control the manufacturing process the components at VCC are measured using Coordinate Measuring Machines (CMM). A typical CMM is composed of three orthogonal axes in X, Y and Z. These operate in a three-dimensional coordinate system. Each axis has a scale system that determines the position of that specific axis. The machine will note the input from the touch probe. The machine uses the X, Y and Z coordinates of each of these points to determine size and position with micrometer precision (Coord3_Metrology 2015).

Critical areas on the parts are on beforehand decided and defined by measuring points. In Figure 20 the measuring points for flush on a XC90 bonnet can be observed. Gap, flush, surface and attachment points are usually measured on parts. These points are defined by tolerances and the process is verified that it is stable by measuring these points (Ohlsson 2015).

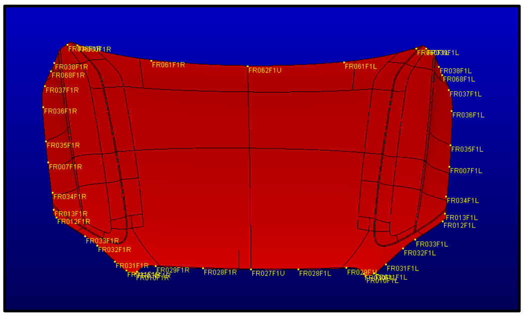

Figure 20 - Measuring points for flush on a XC90 bonnet

The part that is to be measured is positioned with a fixture. The fixture will amplify the variation and it is important that the fixture is controlled before measuring a part. The fixture might have been subject to poor handling. An example of when the fixture can change its settings is that it might have been stored outside where it is exposed to lower temperatures that will make the material shrink. The verification of the fixture is performed by a CMM that measures its settings. The fixture is then calibrated in order to achieve its intended setting. When the condition of the fixture is checked, the operator knows what amplification will come from the fixture and it can then be taken into account in the data from the measuring (Ohlsson 2015).

Measuring accuracy should be chosen in relation to the requirements. It is important that the measuring equipment used is appropriate and calibrated. Variation of the measurement system is characterized by location and width of the spread. The terms Repeatability and Reproducibility are in most cases in focus when discussing the capability of a measurement system to obtain the same measurement reading every time the measurement process is undertaken for the same characteristic or parameter. Repeatability refers to the inherent variation in the measuring equipment and reproducibility is related to whether different appraisers produce consistent results (Bergman & Klefsjö 2010).

There are two different tests to calibrate a CMM. The first is the length measuring performance test, designated as E test. The E test is a test to determine the CMM's capability to measure lengths. The test calls for a series of measurements of calibrated gage blocks or step gages. At least 105 length measurements are performed on seven different positions. The measured lengths are then compared to the calibrated values done by the step gage, deviations must be less than the machine specification for all 105 measurements. The E test is not sensitive to the errors that might be done by the probe. Therefore a probe test, the R test is performed. The R test aims to evaluate the probes precision by measuring a sphere at 25 different points. The test is sensitive to any directional measuring problems with the probe. However the R test does not single out specific problems with the probe but it is useful for finding random or systematic errors with the probe (Salsbury 2002).

When the CMM and fixture are calibrated, the part is measured at the critical points see Figure 21.

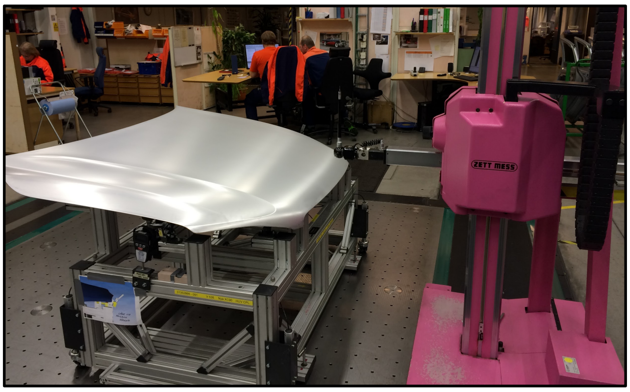

Figure 21 - Measuring of a XC90 bonnet at Volvo Car Body Components in Olofström

The probe that measures the points has a diameter of 2 mm and it is difficult to measure holes that are smaller than 4 mm. The sensitivity of the measuring machines is two to three grams, in other words it will then stop and note the measure see Figure 22. The precision of the measure system is a couple of tenth of a millimeter. It depends on the position of the machine. The precision is better closer to its original position and worse further away when the arms are extended.

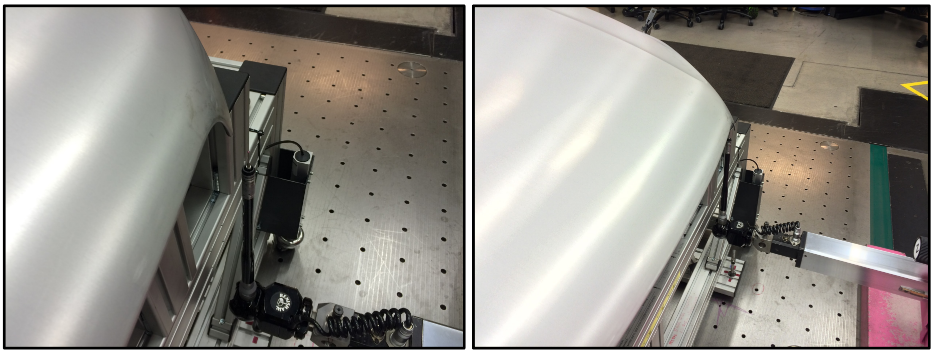

Figure 22 - Measuring of a gap point on a XC90 bonnet

Preferably the locating scheme for a part is the same for measuring and the assembly, to have the same positioning variation. In some cases this is not possible as the fixture might block some areas for the measuring machine or that it might be difficult for the operator to position the part in the fixture that is used for assembly. Instead the part is positioned with a different fixture for measuring, but the values are recalculated in order to give the same results as the fixture used in assembly (Ohlsson 2015). An example of this is the measuring and assembly of the front door for the Volvo V60 where the Z reference points in the assembly fixture blocks some areas for the measuring and it is hard for the operators to position the door against the actual Z points just beneath the window. Therefore the Z points are moved to the bottom of the door as can be seen in the Figure 23. The original Z points are still used as reference.

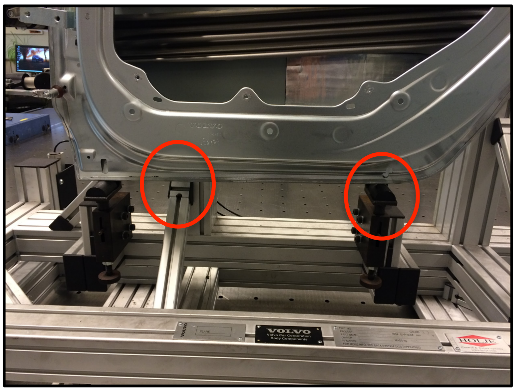

Figure 23 - Z-points for a V60 rear door

CM4D stands for Coordinate Measurement Machine Management Mechanism for Data and is the software where VCC stores all measured data from the factories. From this it is possible to access data about chosen components to use as input to the project and then use as reference data when analyzing the simulated data (Johansson 2015).

3 Method

The master's thesis was an exploratory research on how part related tolerances could be realized. The initial development of the method is described in Appendix 2. This chapter describes the method used during the project and how it was developed.

In the beginning of the project literature was studied to gather knowledge about the subject. This literature research continued along the project but not as intensive as in the startup phase. The findings are presented in the Theory chapter.

Figure 24 presents the main steps of the method used in this project.

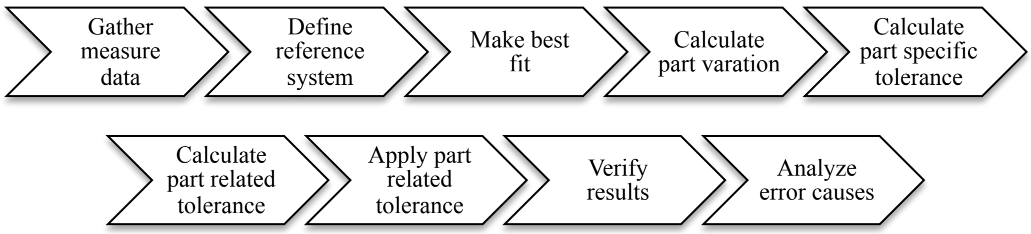

Figure 24 - The main steps of the method

3.1 Gather data

One way to approach the problem was trying to identify a correlation between simulated data and measured data. Initially the idea was to use 3D scanning of parts to gather accurate information about the manufactured parts. 3D scanning allows more precise results than a CMM. It also gives a complete picture of the parts, not only a finite number of points. One benefit among others is that the actual points can be studied, and not where they should have been. This will be further explained in the Discussion chapter. Unfortunately, the scanning equipment was highly exploited and would not provide sufficient amount of statistical data. Further, the intention was to gather data over time and this was possible when using CMM data. It was decided to look at previous measured parts from production and make a best fit to remove the effects from the fixtures. With the parts positioned with best fit it was possible to find the part variation for each part. Data from measurements was available through the software CM4D.

Data about the nominal design and the measures was transferred from CM4D to RD&T. It was important to choose data without shift of the mean depending on changes in the process, see the left plot in Figure 25. The data should also have a horizontal mean and not systematically increase or decrease. The data had to be normally distributed in order to make the simulations as accurate as possible, but most important to give a correct and reasonable comparison between the simulated and measured data. For some parts it was very hard to find good and normally distributed data. That was the reason for starting with small samples, illustrated to the right in Figure 25. Between 10 and 20 samples in a row was possible to assume being normally distributed. In the end larger samples was used. This will be further explained later on.

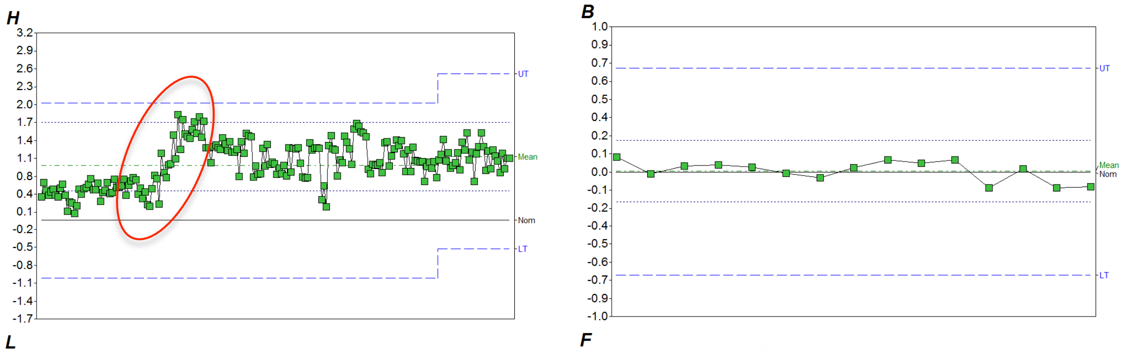

Figure 25 - Left: Large sample including mean shift. Right: Small sample

3.2 Calculate part variation

A locating scheme was defined based on the system description of the part. As stated before a best fit was made to make it possible to minimize the influence of the positioning variation and mainly observe the part variation. When making a best fit the deviations in the points become more similar. The large deviations become smaller and the small ones become larger. There was a function for making a best fit in RD&T, which could be used with some adjustments. It used the least square method to minimize the mean deviation of all points. The current version could only make a best fit of the mean of all inputs, but in this project it was needed to have one best fit for each single measured component. The best fit generated a set of offsets for the locating points to achieve as small deviation from the nominal design as possible.

From the new positions of the locating points the variation of all measure points was calculated with variation analysis. The number of iterations should be the same as the number of valid input data. Using the variation analysis it was possible to calculate the mean of the standard deviations of all points. The sum of 6σ was given by RD&T. The mean of 8σ was calculated. The reason for using 8σ was that a C_p value of 1.33 was used later on, meaning that 8σ should be used as limits in the randomization of numbers. These extracted values were the tolerances from a specific part. These tolerances were all stored in an Excel-sheet. In order to make the best fit as good as possible edge points and surface points were differentiated and compared in different simulations. Edge points were used in the gap simulations and surface points were used for flush.

By investigating different car models it was possible to calculate different means of the standard deviation. These were compared and a mean of them was calculated. This mean was then the part related tolerance found for each component respectively.

3.3 Applying the part related tolerance

The found part related tolerance was verified by deleting all existing tolerances in the RD&T models and instead applying tolerances with a range equal to the found part related tolerances for each component and car model expressed in 8σ. For example the front doors of the tested car models had one tolerance for gap and one for flush and the rear lamps had others.

Important to notice is that the applied tolerances in the locating points were of the same type in the different simulations. For example, in the case with the door the Y reference points were surface points and the flush tolerance was applied to these in both gap and flush simulations. Similarly, the X and Z reference points, which were edge points, got the gap tolerance for the simulations. For the bonnet the Z reference points were surface points and had flush tolerance and the X and Y had the gap tolerance.

After the tolerances had been applied a variation simulation could be made for each component. The results were plotted together with the measured data. Appendix 3 includes the Matlab code for this action. The intention was that the values should be close to each other. For some components this was not the case and the project team contacted experts to get support in finding the causes of the differences. The team also visited the measure room in Olofström where the majority of the measured data in this project comes from.

3.4 Studying large sample data

In the phase of identifying error factors it was realized that the samples were probably too small. The team worked with finding a solution to the mean shifts and found a way to handle it. Instead of looking at the whole sample it was possible to divide the sample into smaller groups with three to five measures in each group. Each measure was part of several groups, see Figure 26 below. Then the shift of the mean would not be very significant. There are two types of variation: within-group variation and between-group variation. For this problem it was assumed to be enough with looking at the within-group variation. The standard deviation for the group was calculated and then the window was moved one step and the procedure was repeated. The mean of the standard deviations of each group could be considered as being the standard deviation of the sample. This was done for all measure points on a component.

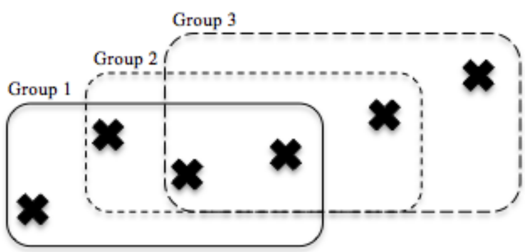

Figure 26 - Dividing the sample into small groups

A window size of three, four or five measures was used. It turned out that the results were very similar and four was chosen for this project. Figure 27 illustrates the difference.

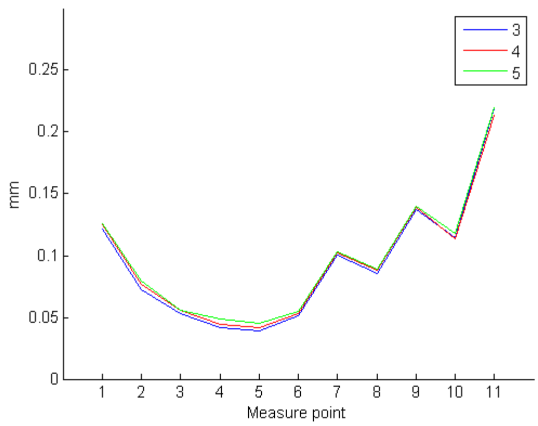

Figure 27 - Different window sizes

To minimize the effect of large mean shifts the standard deviations were plotted in a control chart and the control limits announced when the standard deviation was too large to be relevant. Figure 28 shows the Xbar-chart and s-chart for one of the points of the XC60 rear lamp flush. The Xbar-chart shows the mean of each group and the s-chart shows the standard deviation of the groups. It is clear that even though the mean changes, the standard deviations are similar. This means that the mean shifts are eliminated. The points outside the control limits in the s-chart were eliminated. The results were then plotted with each simulated model again. A best fit with the new data was not made due to time restrictions and it was previously shown that a change in the tolerances did not affect the result much for the simulated curves. Using a part related tolerance or a model specific tolerance showed almost no difference. The curve was offset slightly and the shape was amplified a bit. But in general they were very similar. Therefore it was decided not to redo the best fit.

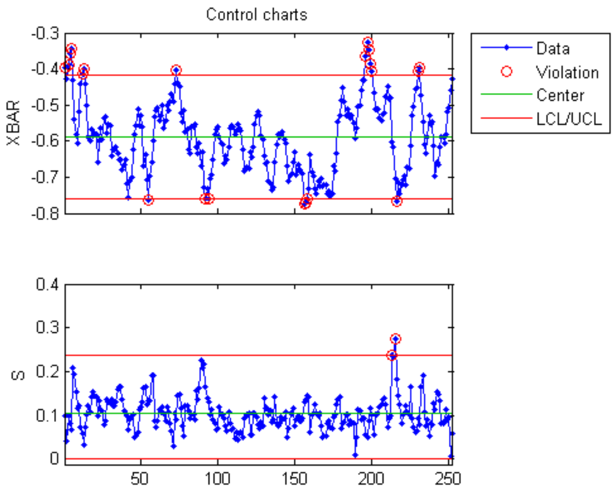

Figure 28 - Xbar- and s-chart for one of the flush points of the XC60 rear lamp

Calculating the control limits and removing the outliers could be iterated to increase the precision even more. It was realized that it would not be needed. Therefore, only one iteration was done. Figure 29 show the difference between not removing outliers, do one iteration or do two iterations.

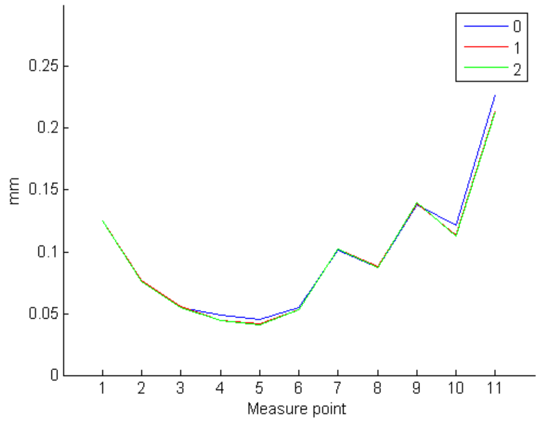

Figure 29 - Different number of iterations

The procedure with transforming the measure data from text to numbers, calculating the deviations and sort out the relevant data was done in Matlab. The code is presented in Appendix 3.

The process was expanded with the steps shown in Figure 30.

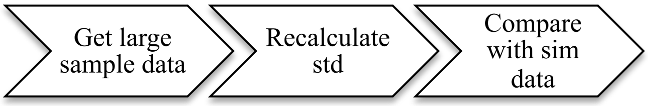

Figure 30 - The expanded process

3.5 Mapping error causes and the need of the function

One part of the project was to identify which error causes that were present and how they could affect the result. This was especially done after the small samples did not give many promising results. These are described in the Discussion chapter.

Also the need of the function and how it could be implemented into RD&T was explored. Through semi-structured interviews a lot of information was gathered.

4 Results

This chapter presents the results found in the project. The first part is based on the small samples and the prerequisites are submitted. The second part continues with the results from the large samples, which were discovered in the end of the project. The last part of the chapter focuses on the need of and suggestions for the function of using part related tolerances. Appendix 4 includes translation tables, which allow translation between the plots and the measuring points of each part.

Correlation is said to exist when the curves behave similarly and when they are around the same size. This is based more on intuition than on calculations.

4.1 Comparison using small samples

This chapter presents the results from the small samples and discusses possible reasons for the behaviors.

4.1.1 Bonnet

At first a bonnet of a Volvo XC60 was studied. Figure 31 shows the feature grid of the bonnet. The feature grid specifies the nominal position of the measure points and the vectors in which the tolerances act respectively. The surface points in the middle were not considered. Onto this a data grid was applied with deviations in each sample. This created a set of points with deviations in respective direction.

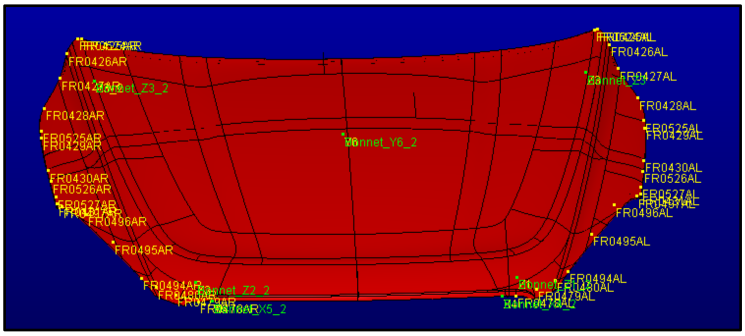

Figure 31 - Feature grid of the XC60 bonnet

The first results were not satisfactory at all. The visit in Olofström explained why. The bonnet is measured with four locating points in Z. This is because the bonnet is not rigid and needs extra support point. To make a compliant simulation would be beyond the scope of this project and it was decided to use alternative assembly, which is often used by the robust design engineers at VCC. This means that different locating schemes are used for different measures. The bonnet was divided into two parts, left and right. Figure 32 displays a typical reference system for a bonnet. The exact coordinates are different for different models but the main idea is the same. For the points on the left side (to the right in Figure 31) Z_1, Z_2 and Z_4 were used as A-points. For the right points Z_3 was used instead of Z_4. This created symmetry and the behavior of the simulated data was much calmer than with only three locating points in Z.

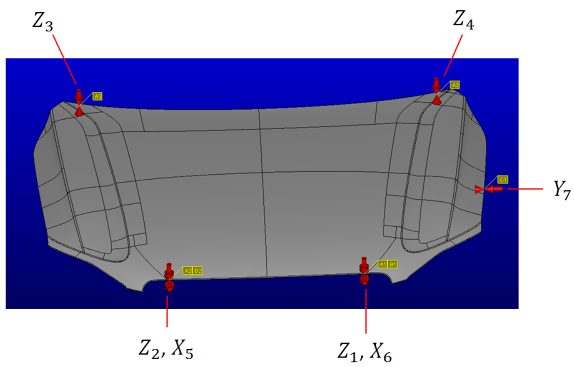

Figure 32 - Typical reference system of a bonnet

The applied part related tolerance was the mean of the deviations of the XC60, the V40 and the new XC90 bonnets. The XC90 was still being developed during this master's thesis and the data that was used would eventually not be able to mirror the data from when it is being mass-produced. The means of 8σ in millimeters for the different models are shown in Figure 33 and presented in Table 1.

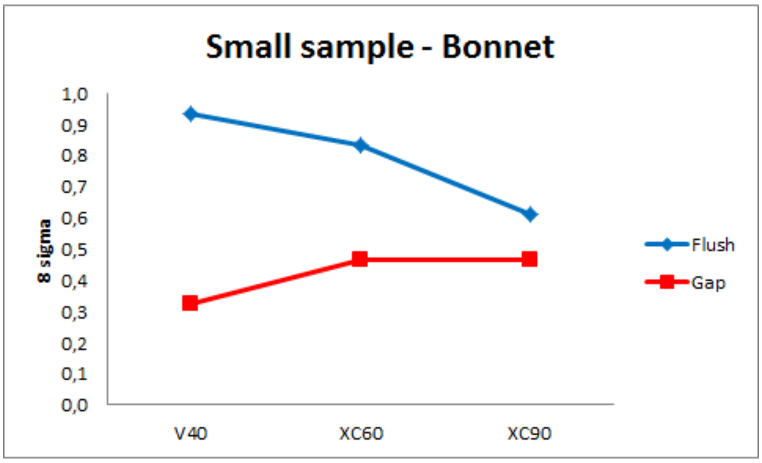

Figure 33 - Part specific tolerances of bonnets

Table 1 - Part specific tolerances of bonnets

Model	Flush (mm)	Gap (mm)
V40	0.933	0.325
XC60	0.830	0.463
XC90	0.610	0.463
Average	**0.791**	**0.417**

The Z points are affected by deviations in flush direction, the applied tolerance is the flush tolerance. For the X and Y, the gap tolerance is used based on the same reasoning. Figure 34 and Figure 35 show the comparison between the simulated and the measured six standard deviations. 6σ are used throughout the report since it is used for these kinds of measures in industry.

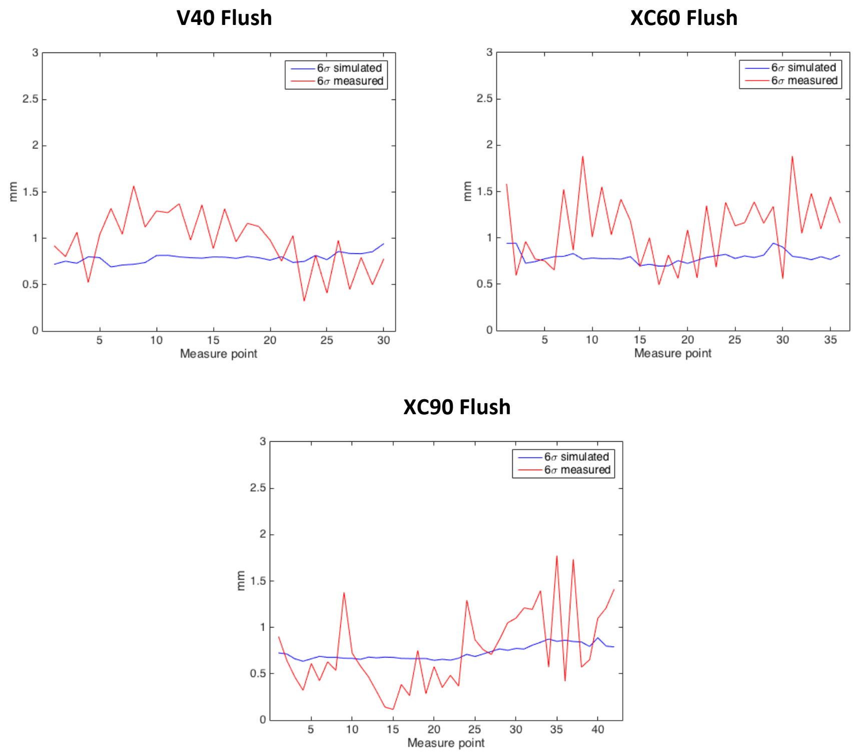

Figure 34 - Flush of bonnets

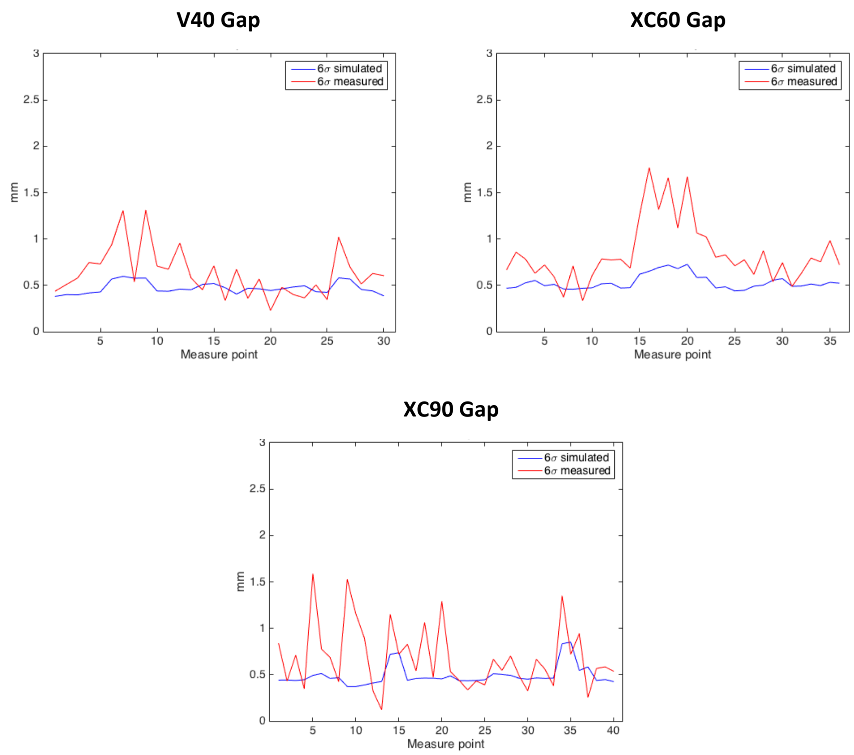

Figure 35 - Gap of bonnets

As shown in the figures the curves behave similarly in some points. But the measured data is much more disorderly than the simulated data. In some points there seem to be a small negative correlation, meaning that the measured value is high when the simulated is low and vice versa. But for some points there seem to be a small correlation.

One possible factor affecting the measured results is “cracking”. This means that the manufactured components are cracked to make the component fit better. This is a much cheaper method than purchasing new tools and changing the main process, as only small adjustments have to be made. This affects the measures and might be one reason for the differences in the plots. The XC90 bonnet is not cracked and still it does not give plots that correlate with the simulated data. There are probably other factors affecting the measures as well. Some of these are further discussed in the Discussion chapter.

For the bonnets it was hard to identify a clear correlation. Some points are promising but some points are far from each other. It was decided to investigate a more rigid part. The front door was to be looked into.

4.1.2 Front door

Just as in the case with the bonnets best fit was used for positioning the doors and calculating the part variation. The means of the deviations were calculated and applied to the models. The initial plots, where only one model was studied, showed promising results and more car models were used for finding a part related tolerance. The different car models were V40, V60, V70 and XC60. Figure 36 and Table 2 show the tolerances for each model respectively.

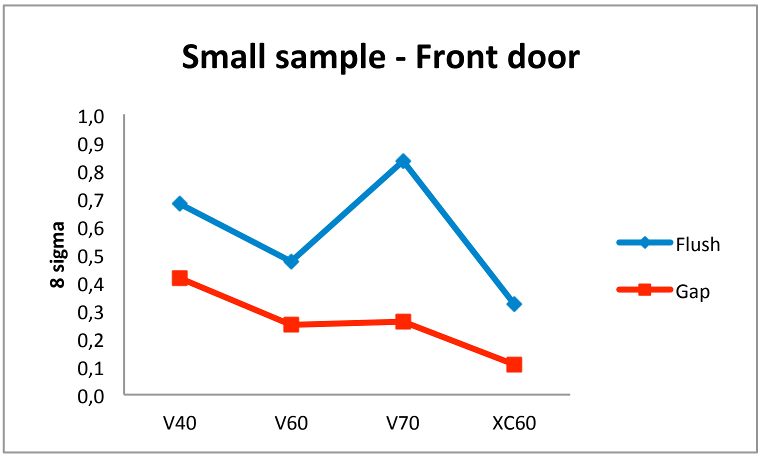

Figure 36 - Part specific tolerances of front doors

Table 2 - Part specific tolerances of front doors

Model	Flush (mm)	Gap (mm)
V40	0.680	0.415
V60	0.475	0.250
V70	0.833	0.261
XC60	0.321	0.107
Average	**0.577**	**0.258**

The typical reference system for a front door is viewed in Figure 37.

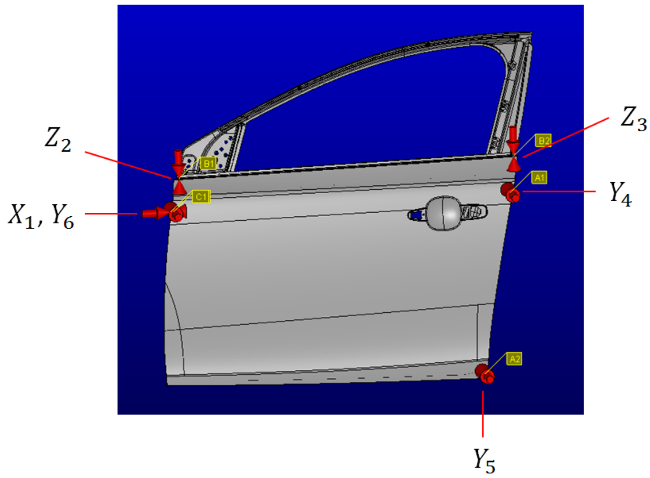

Figure 37 - Typical reference system of a front door

The part related tolerances were applied on each model and all tolerances from previous simulations with measure data were removed. The door was positioned with a 3-2-1 locating scheme. There are three Y, two Z and one X reference points. Ys are surface points and should have the part related tolerance from the flush simulations and the X and Z are mainly controlling the gap meaning that they should instead have the part related tolerance from the gap simulations. It is the same reasoning as for the bonnets but the door is positioned in another direction than the bonnet and Y is used for flush instead of Z.

The results from the variation analysis of the found part related tolerances for flush are shown in the plots in Figure 38.

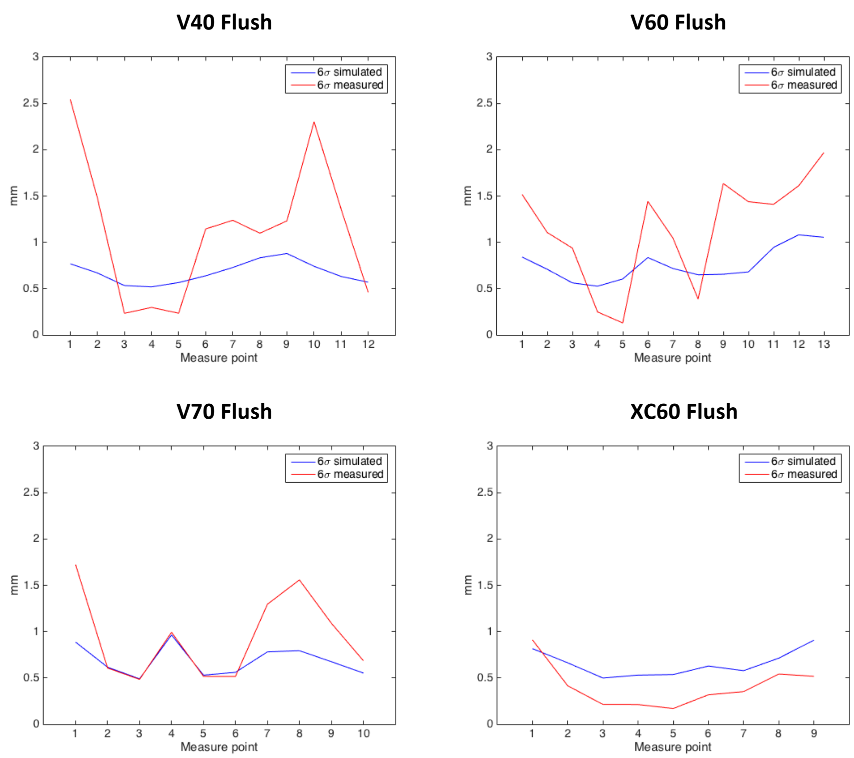

Figure 38 - Flush of front doors

It seems like there is more correlation for the doors than for the bonnets. For some models, like the V70 flush, the simulation with part related tolerances seem to work well. The points 7-9 on the V70 flush are located in the lower front corner on the door, which is far from the locating points in Y. These are not correlating very well. The same thing goes for the V40 where point 1 and 10 is located in the same corner. In points 8 and 9 of the V40 flush there are smaller deviations in the measured data and larger in the simulated. These points are located on the top of the back arch and should logically have a greater variation than points 6 and 7 which are closer to the reference points. The simulated data shows the expected behavior but for the measured data this does not seem to be the case. The explanation is that when driving fast an under pressure is created outside the car and to avoid leakage or wind noise the back arch is cracked. This reduces the variation in the nearby points. Fredrik Wandebäck and Per-Johan Wahlborg at Swerea IVF claimed that it might be possible that the variation increases somewhere else even though it reduces locally (Wandebäck och Wahlborg 2015). The V60 flush simulation does not give very good results. There are some points where the measured data deviates a lot from the rest of the points. The simulations are smoother which means that the standard deviation is more similar in all points.

The results from the variation analysis of the found part related tolerances for gap are shown in the plots in Figure 39.

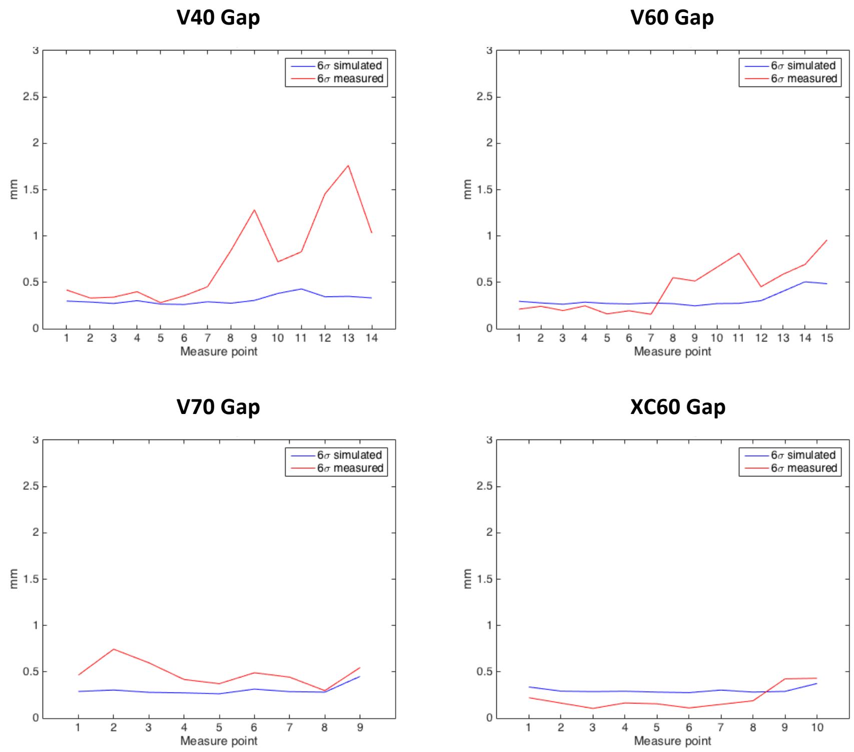

Figure 39 - Gap of front doors

The gap variations are generally smaller than the flush variations. This was also expected. Smaller variations seem to correlate well than when the measure data have higher values than the simulated data. For the gap where the variation is smaller the simulated and the measured data are similar. Most of the points have a difference smaller than 0.2 mm. The precision of the measure system is approximately the same and that would mean that the simulations are promising.

One reason for getting better results from the doors than from the bonnets could be that the triangle that the reference points defining the plane (Y for the doors and Z for the bonnets) is smaller. Inside the triangle the part is not very sensitive to variation. Outside, it becomes more sensitive further away from the triangle. This means that the door has a less robust positioning system and the variation is amplified more than for the bonnets. The door is also more rigid than the bonnet.

In order to increase the precision of the simulations a small adjustment was made. The part related tolerance was replaced with the model specific tolerances found with the best fits. Those values were previously used for calculating the mean which became the part related tolerance. It turned out that the simulated plot only moved a couple of tenth of a millimeter and the shape of the curve was subject to a tiny amplification. Hence, it did not contribute to finding a correlation. It was decided to continue with the part related tolerances since the purpose of this project was to investigate a correlation and not quantify the tolerances.

After these results were found the project team visited Volvo Car Body Components (VCBC) factory in Olofström, where most of the components used in this project are manufactured and measured. The intention was to gain the understanding of the process and try to identify factors contributing to errors in the measures. Information from the factory visit is presented further in the Discussion chapter.

4.1.3 Rear lamp

The rear lamps that were investigated were from the car models: V60, S60, V70, XC60 and the new XC90. During a long period of this project the S60 was given an incorrect locating scheme, which affected the results. Therefore it was treated separately. The best fit was not affected by the locating scheme and the part specific tolerance was correct. When the incorrectness was discovered it was still handled separately to minimize the rework. As claimed before the plots were not affected much by working with generic part related tolerances or part specific tolerances.

Figure 40 and Table 3 show 8σ of the rear lamps.

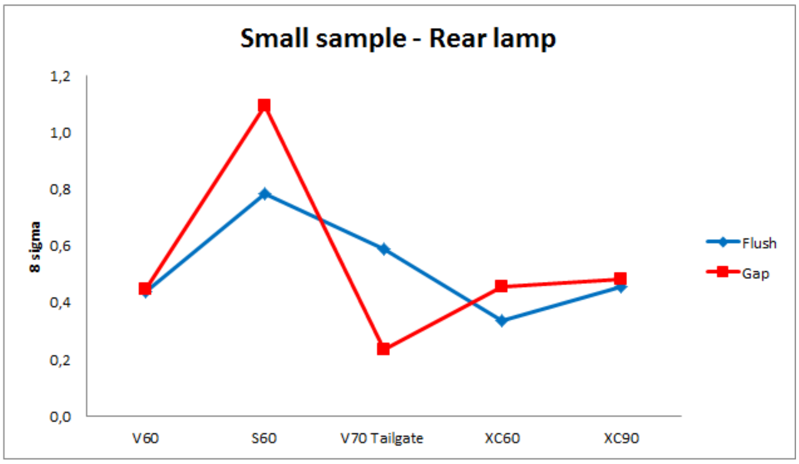

Figure 40 - Part specific tolerances of rear lamps

Table 3 - Part specific tolerances of rear lamps

Model	Flush (mm)	Gap (mm)
S60	0.781	1.092
V60	0.439	0.445
V70 Tailgate	0.585	0.231
XC60	0.336	0.453
XC90	0.453	0.482
Average	**0.519**	**0.541**

Figure 41 shows the characteristic locating scheme for a rear lamp.

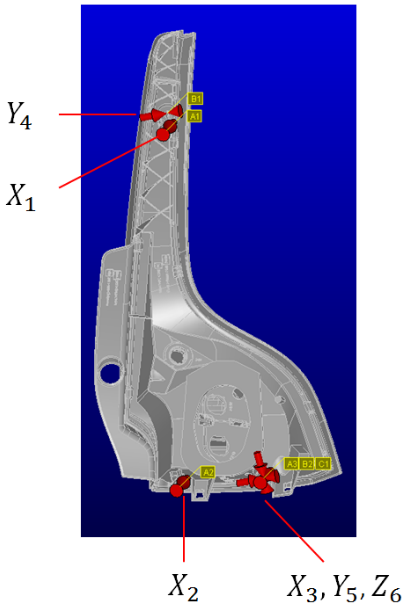

Figure 41 - Typical reference system of a rear lamp

The lamps were positioned according to their respective system description. It uses three X points, two Y points and one Z point in order to lock it in space. The lamps have a slightly angular shape and the different locating points have vectors that do not effectively lock each direction. It is for this reason that the V40 lamp was discarded as it has reference points that does not use the 3-2-1 locating scheme in an efficient way. Flush values were put on the X point and gap values on the Y and Z points. The found part related tolerance from the V60, V70 tailgate, XC60 and XC90 was then simulated and plotted against the measurement data from CM4D. The plots for the flush measures can be seen in Figure 42.

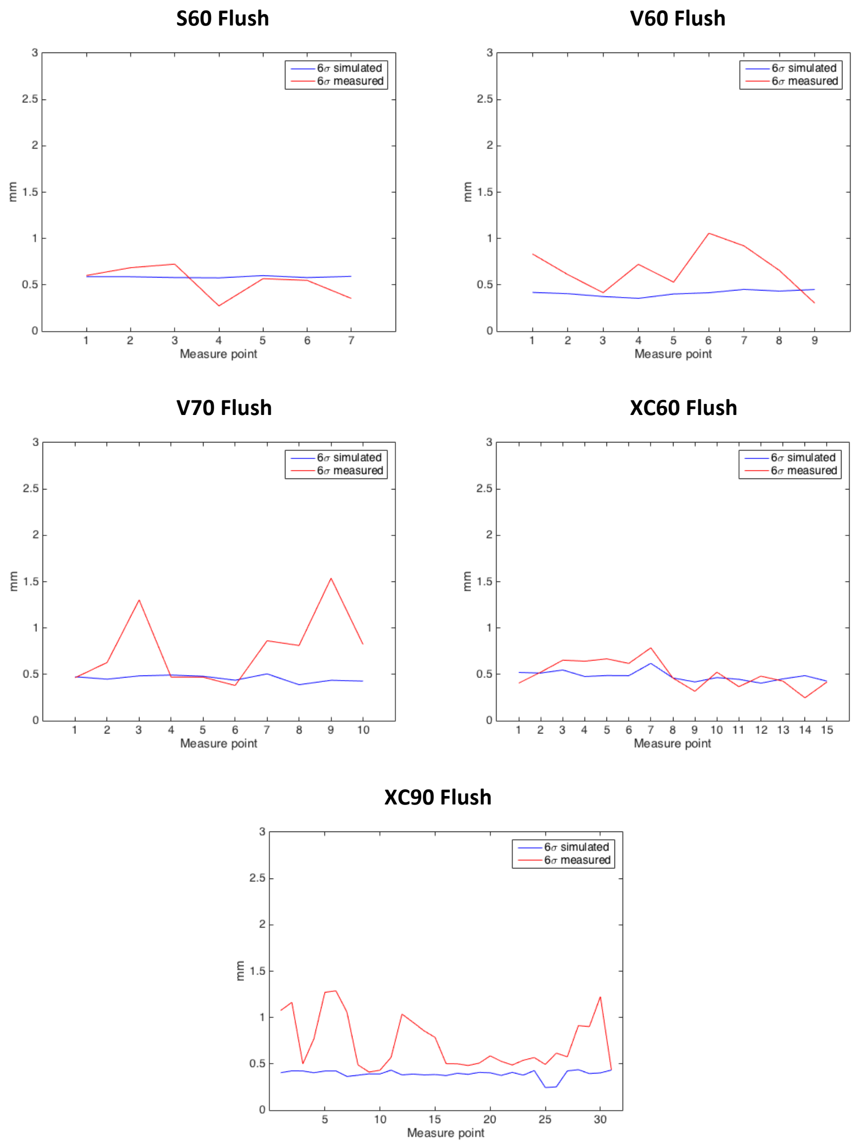

Figure 42 - Flush of rear lamps

The results from the flush simulations show overall little correlation with the measured data. Promising is the XC60 plot where the curves almost behave in the same way. The biggest difference between the two curves is about 0.2 mm, which is the error marginal the CMM has. For the V70 there is correlation between the measure points 1 and 4-6, and points 7 and 8 have some correlation even though the sizes of the standard deviations are not similar. But in the other measure points there is not much correlation. Worth noting is that the XC90 currently has 31 flush measure points to control that its process is stable and therefore the curve looks a bit different. After the right locating scheme was implemented the simulated and measured results of the S60 were rather similar.

The plots for the gap measures can be seen in Figure 43.

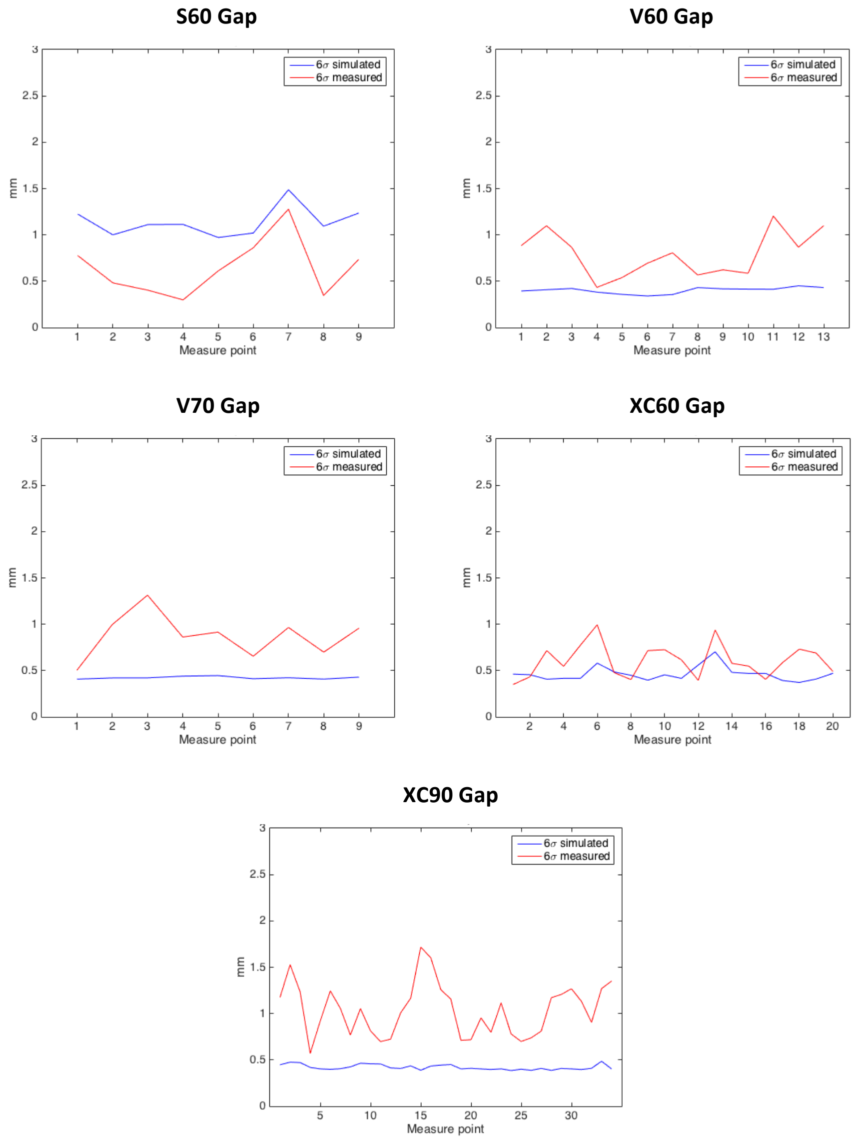

Figure 43 - Gap of rear lamps

Again the XC60 shows promising results, as the measure values often are the same. However, there are some differences. The simulated curves of the V60, V70 and XC90 show the same kind of behavior, but the measured curves of these models show no indication of similarities with the simulated ones.

The conclusion that can be drawn from the investigation of rear lamps with small samples is that a part related tolerance might not be possible for these. Molding of plastic seems to be an unpredictable manufacturing method. This changed when studying larger samples.

4.1.4 Rear door

As the left front door gave promising results it was decided that the left rear door of the car models S60, V40, V60, V70 and XC60 should be investigated. 8σ of the rear doors are shown in Figure 44 and Table 4.

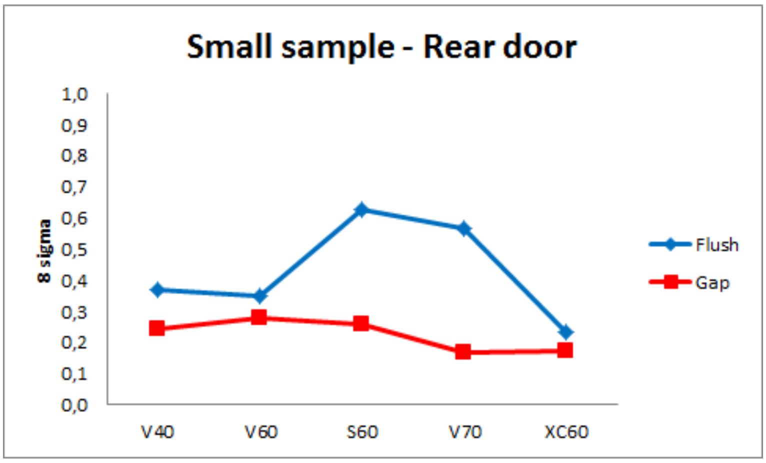

Figure 44 - Part specific tolerances of rear doors

Table 4 - Part specific tolerances of rear doors

Model	Flush (mm)	Gap (mm)
S60	0.625	0.257
V40	0.366	0.243
V60	0.347	0.279
V70	0.564	0.168
XC60	0.231	0.172
Average	**0.426**	**0.224**

The typical reference system of the rear door is similar to the one on the front door. Figure 45 illustrates this.

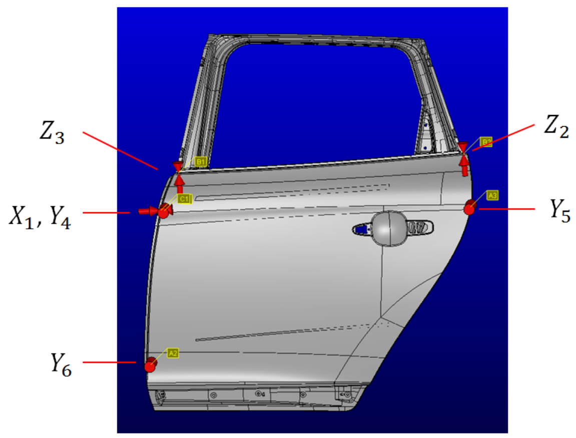

Figure 45 - Typical reference system of a rear door

The flush plots are presented in Figure 46.

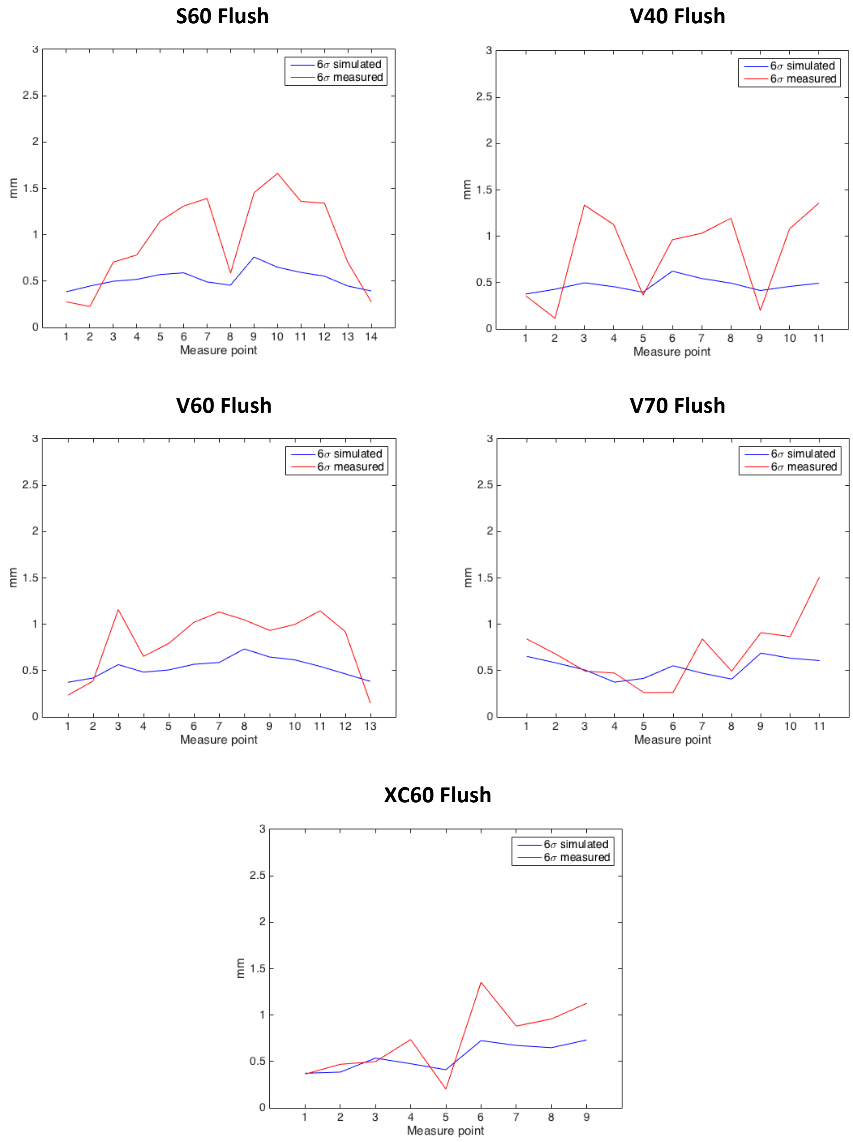

Figure 46 - Flush of rear doors

For the models V60, V70 and XC60 the curves show similarities between the measured and the simulated data. The curves have somewhat the same behavior and some of the values on the measure point are the same for both curves. The S60 and V40 plots do not show a clear correlation between the two curves. All in all the rear door shows a rather good correlation in three out of five plots regarding the flush measures.

In Figure 47 the gap measures of the simulated and the measured data can be seen.

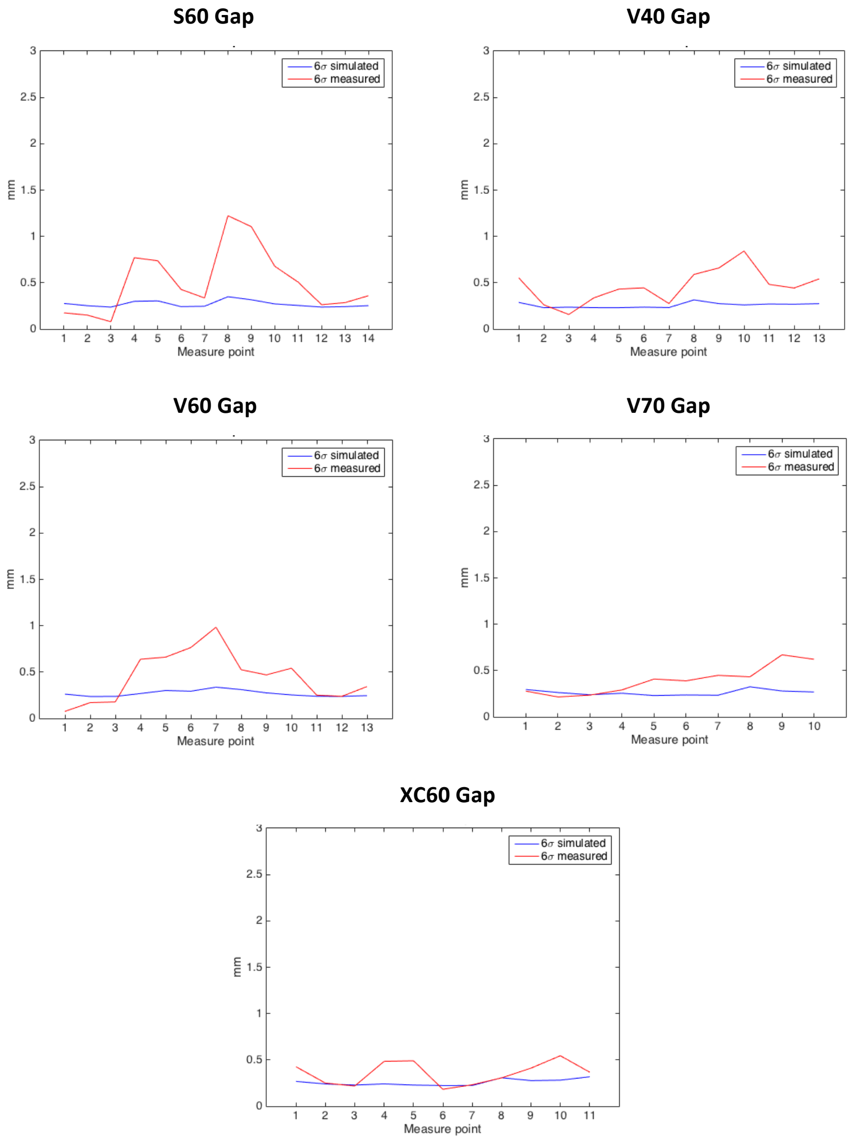

Figure 47 - Gap of rear doors

In the V70 and the XC60 gap plot there are some correlations between the two curves, but the measured data deviates from the simulated data in a few points. This might be due to that the fixture that it is measured in is less robust than the system that is used for positioning it in RD&T. The V60 and S60 plots show the largest deviation between the measured and simulated curves, and give almost no indication of correlation. Otherwise the curves show a correlation and they are around the same size. It is also worth noting that the simulated curves look almost the same for each model, with a straight shape of its curve. This is indicating that in RD&T the positioning system is robust for the X and Z points.

4.2 Large samples using standard deviation in small steps

As stated in the Method chapter the small samples were considered being a factor that could affect the results. That turned out to be the case for some components. Especially for the bonnets it was hard to draw any conclusions. Larger samples were tested and the standard deviations were calculated in small steps over the sample and the mean of these were calculated. One mean for each point was calculated. They were plotted together with the simulated data. The plots are presented below. In Appendix 5, a comparison between the small sample and large sample plots is presented.

4.2.1 Bonnet

The bonnets have smoother curves than before. For the flush it is still hard to find a clear correlation. Dag Johansson claimed that this could be because of the cracking (Johansson 2015). The gap plots show that a correlation seem to exist. In both cases the means of the simulated data and the measured data are approximately the same. The XC90 did not have a large number of measures and all available measures were used. It was around 70 measures compared to around 300 for the rest of the components.

Below, the flush plots are presented in Figure 48. The V40 plot shows that the curves do not have a particular correlation as the curves have different characteristics. It is an improvement from the small sample data set and it is considered that this method should be used when trying to find a part related tolerance. The XC60 plot does not show a correlation between the curves, but it is as the V40 an improvement over the small sample data set. The measure points have roughly the same values, which are promising.

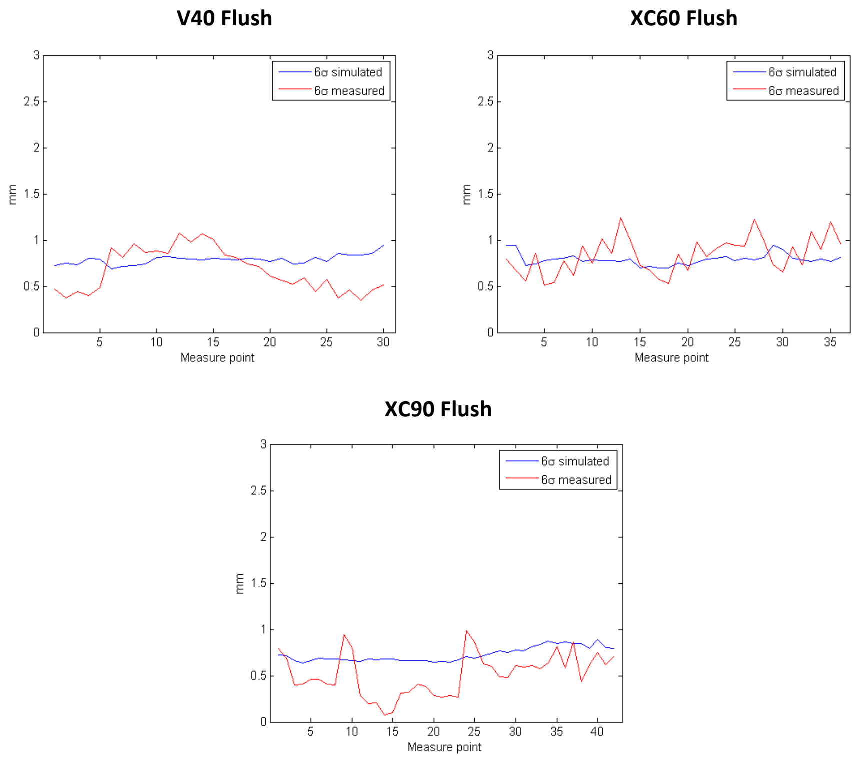

Figure 48 - Flush of bonnets

The gap plots for the car models V40, XC60 and XC90 is viewed below in Figure 49. In the V40 plot the simulated and the measured curves show a clear correlation as they have almost the same shape. From the point 18 to 25 the curves are offset to one another but the difference is not large. In the XC60 plot the two curves show correlation. In the point 15-23 the measured curves has a leap but the simulated curves also increase in these points but not as much.

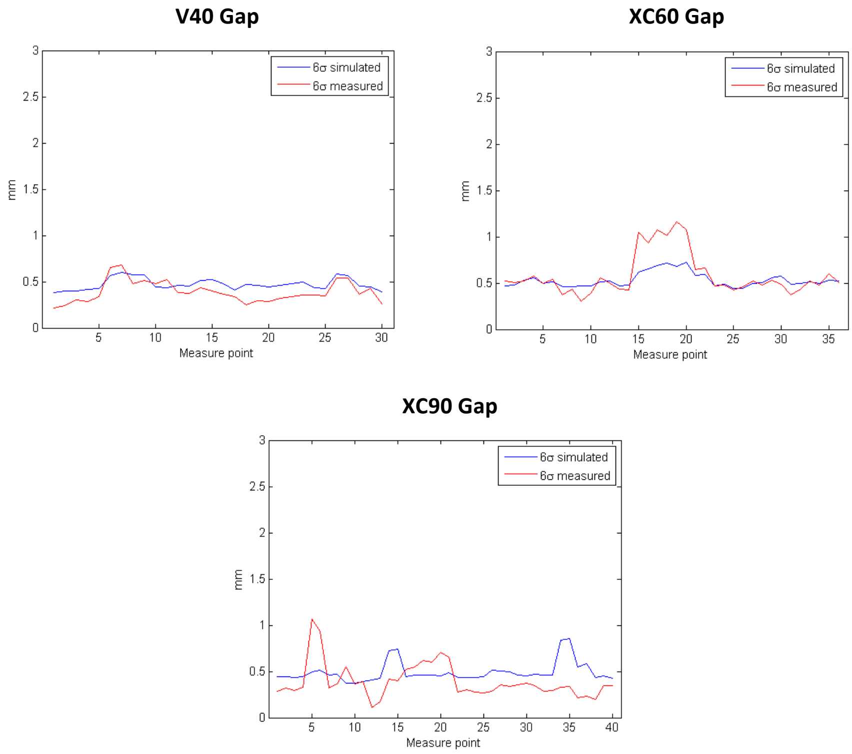

Figure 49 - Gap of bonnets

The XC90 do not show a clear correlation. The process was not very stable at the time, which was affecting the measure data. However, the data was normalized with the new method making the standard deviations more stable. Figure 50 shows an example of a control chart of one measure point of the new XC90. It is clear that the method works and the standard deviations are not affected much by mean shifts. As in the other cases the outliers in the s-chart were removed. Therefore the measure data in the plot above should be rather trustworthy.

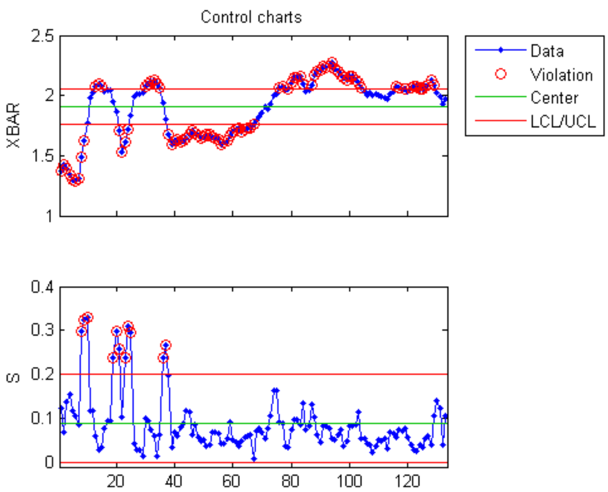

Figure 50 - Control chart illustrating the results of the new method

4.2.2 Front door

In Figure 51 and Figure 52 flush and gap plots for the front doors can be viewed. They show almost the same result with small and with large samples. They show similar behavior and size. One theory of why this is could be that the reference system is worse than for the other components, as already stated. A smaller part of the component is within the triangle of the reference points meaning that the variation is amplified. This increases the influence of the positioning variation. Just as in the case with the bonnets, the gap plots are more promising than the flush plots.

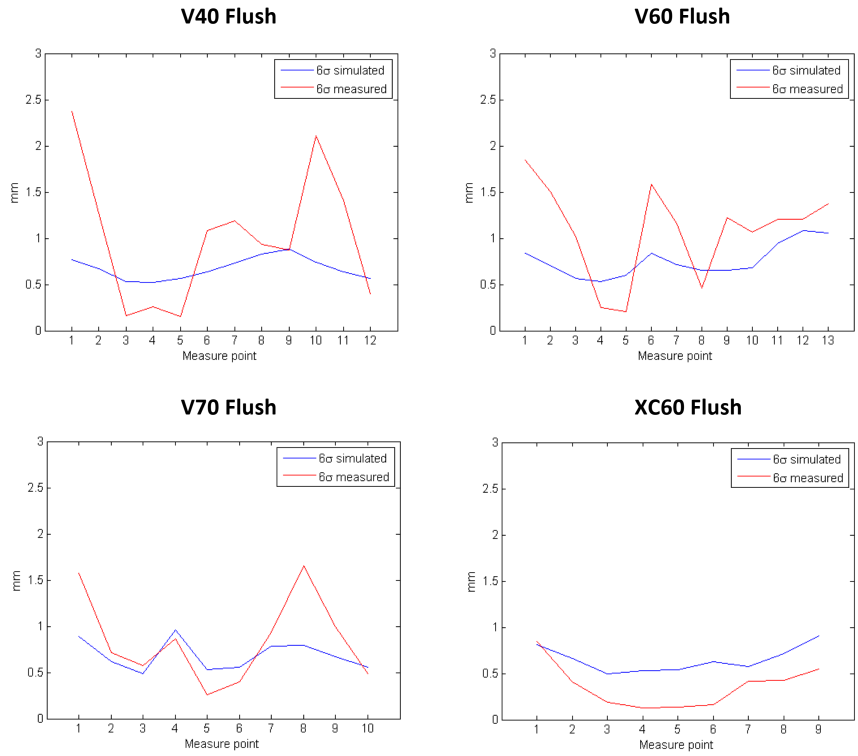

Figure 51 - Flush of front doors

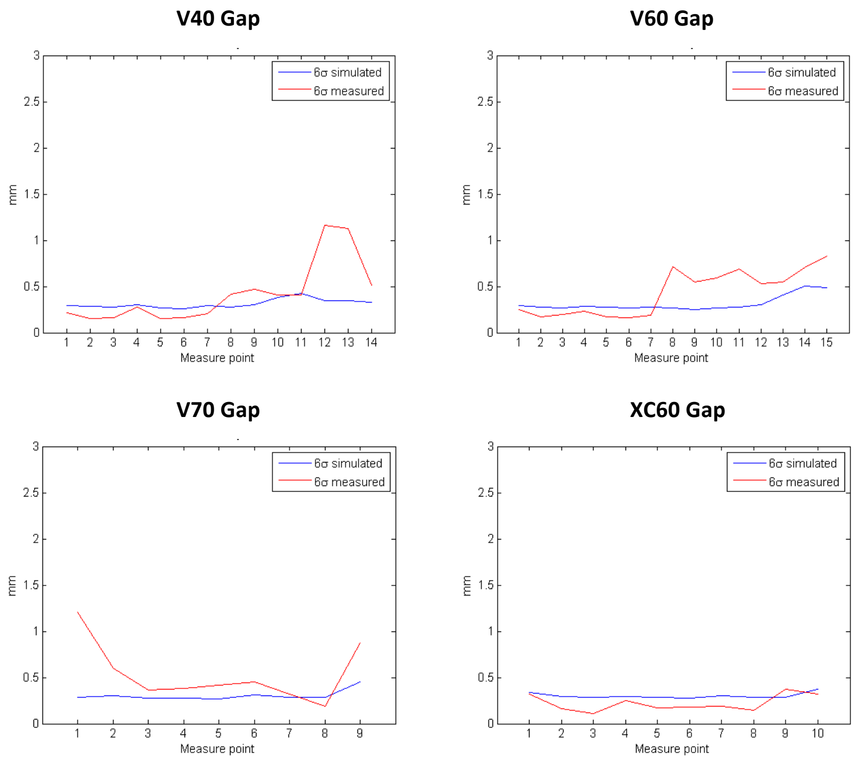

Figure 52 - Gap of front doors

4.2.3 Rear lamp

Treating the CM4D data with the mean shift removal method gave the result for flush measures presented in Figure 53. This gave promising results for the flush measures, in contrast to the bonnets and the doors, which had promising gap values. The new XC90 did not have samples large enough to be considered here. The V60 plot shows that the curves have some correlation in the first five measure points and after that the measured curve shows a trend of increasing standard deviation and the simulated curve remains unaffected. The offset between the measured and simulated curves for the V60 plot is at its largest point 0.5 mm. The rest of the points offset vary between 0.2-0.4 mm. The V70 plot shows that the curves do not correlate much as the simulated curve has a straight shape while the measured curve has a different shape. What is promising is that the difference in values between the two curves is not particularly large and at some points the measure points return the same value. The S60 and XC60 plots show the most promising results where the curves behave almost the same.

The results of the rear lamp gave a more fortunate result when the sample size was increased.

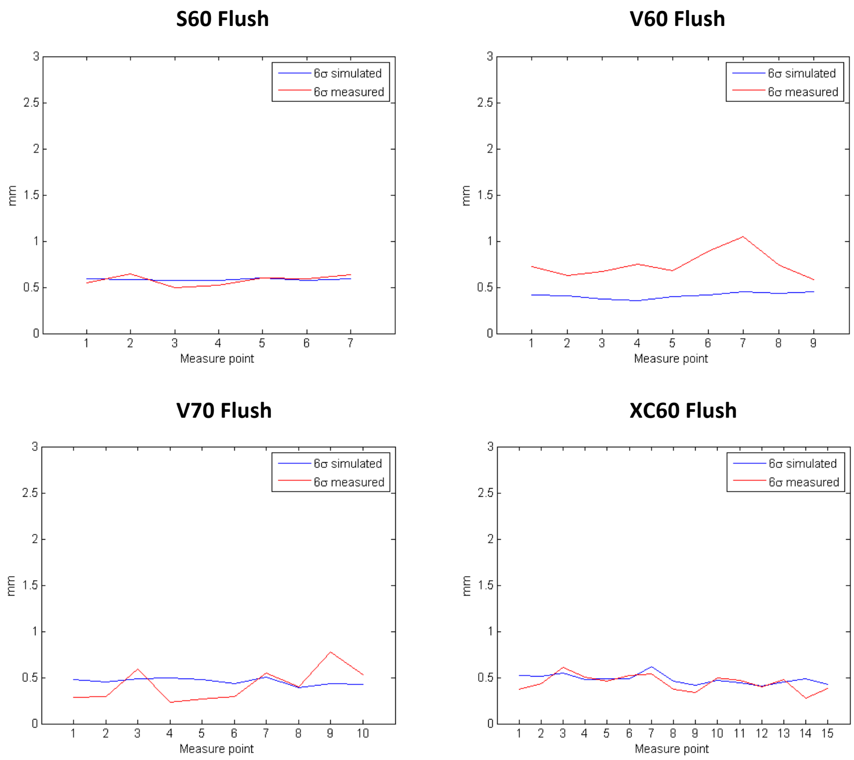

Figure 53 - Flush of rear lamps

The gap measures can be seen in Figure 54 below. The V60 plot shows some correlation in the points 4-9 and little or no correlation in the rest. The difference between the two curves' values is at some points (4 and 13) up to 0.5 mm large and at the points 4-9 the values differ with 0.1-0.2 mm. The V70 plot shows a very clear correlation between the two curves but the measured curve differs slightly in the points 1, 6 and 9. The measure points have almost the same value for every measure point. The XC60 plot shows that the measured curve has an unstable behavior but the simulated curve seems to follow to some extent and achieves correlation in most of the points. The values of the two curves are also the same on several points. In the case with the S60, which showed favorable results for the flush, it is not as promising with the gap values.

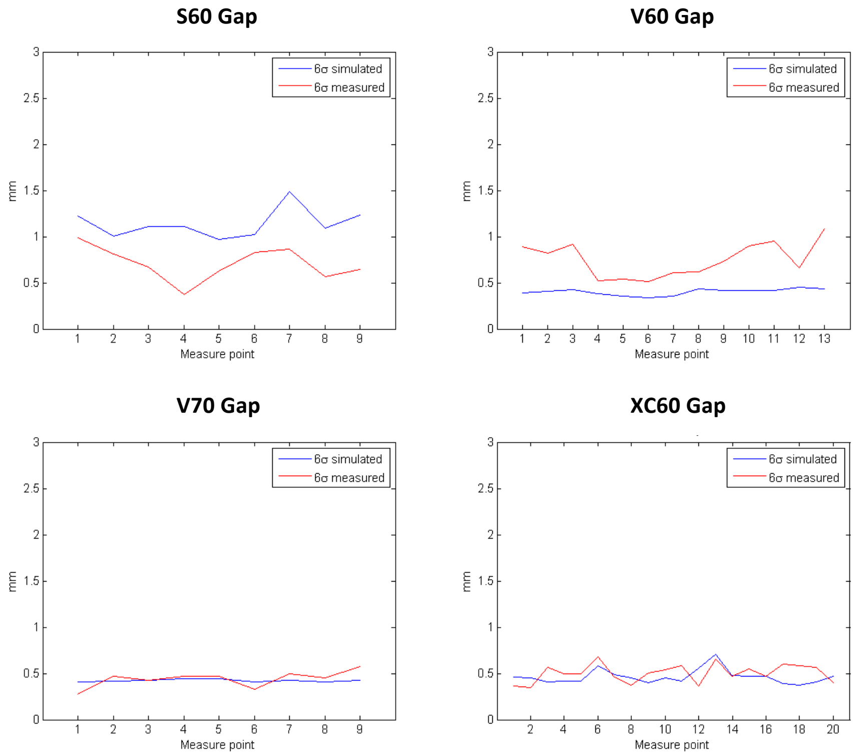

Figure 54 - Gap of rear lamps

4.2.4 Rear door

In Figure 55 below the flush curves of the rear doors can be seen. The rear doors act similar to the front doors. The small and the large samples give almost the same results. Already the small samples showed promising results. For the flush measures it can be concluded that the V70 and the XC60 show correlation between the measured and the simulated curves. In the plots for the car models S60, V40 and V60 the difference are much larger and there is bigger differences in the measuring points. But the curves do behave the same in some aspects. The V60 curves show that they follow each other to some extent.

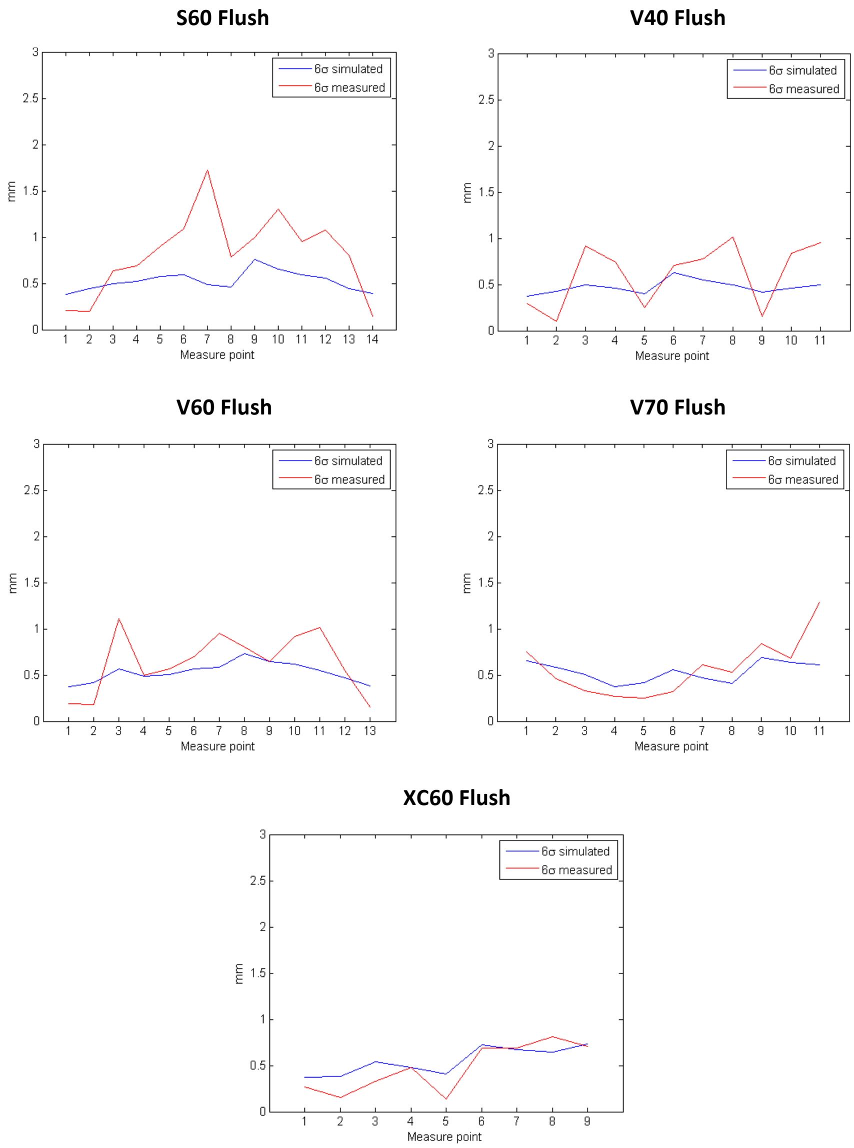

Figure 55 - Flush of rear doors

The gap plots are shown in Figure 56. For all the simulated curves it can be stated that these behave the same, indicating robust locating schemes. Based on the previous results it is hard to see correlation when the simulated curves show no amplification in the different measuring points.

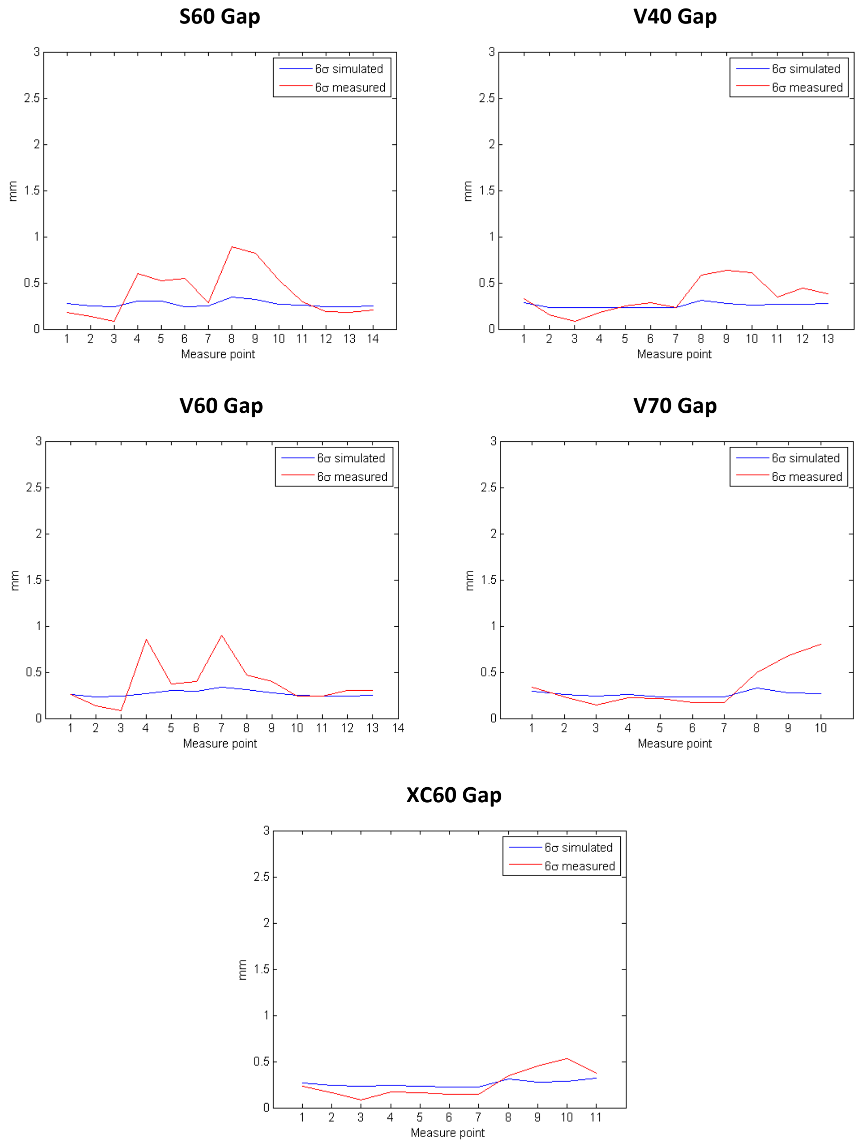

Figure 56 - Gap of rear doors

Overall the new way of treating the sample seemed to make the simulated and the measured curves behave more similar than for the small sample data sets. It was considered that this should be further investigated and evaluated in order for part related tolerances to be implemented as a standard function in RD&T.

4.3 Need of the function

One part of this master's thesis was to investigate the need of the new function. The new function would as described in this report provide part related tolerances of part variation based on, among other things, shape and material. This would increase the accuracy in the simulations and reduce the need for manual work.

Mikael Rosenqvist (Operational manager at PE Geometry) working in the field of geometry assurance said that it would be very interesting to investigate from a technical and academic perspective. And if it saves time for the engineers it is even better. One thing that should be taken into account though, is that automating too much can lead to lost skills of the engineers, which might be a problem if new materials or shapes are investigated. But investigating the possibility to implement it would be very interesting. (Rosenqvist 2015)

The supervisor of this project, Dag Johansson, initiated the project because he wanted to know if there is a possibility to draw conclusions about part variation and part related tolerances. He is a technical expert and knows well what the department working with geometry assurance needs. Several times he stated that he wants more accuracy in the simulations to make them mirror the reality even more. (Johansson 2015)

Peter Edholm (President at PE Geometry) also claimed that it is very interesting to look into this matter. It makes much sense if it is possible to prove that it works. However, it is probably complicated to find general results. The results of this project would only be true for the studied manufacturing methods. Edholm also stated that it might be good to look at different stages of the process. Much can happen along the process so checking after each step would be preferred. He also explained that some suppliers try to manipulate the measure data to eliminate the red numbers. This is something to be aware of even though it is not very common. (Edholm 2015)

Fredrik Wandebäck (Geometry assurance Project leader at Swerea IVF) and Per-Johan Wahlborg (Geometry assurance Area manager at Swerea IVF) said that it might be hard to use part related tolerances, at least for components. The world is so full of variation that it would probably not be easy to describe the variation with generic part related tolerances. Then they added that for final requirements of a product it might be a good idea. On the question if there is any use of part related tolerances they answered that the robust design engineers probably would have use for them. According to Wandebäck and Wahlborg the question "What happens when materials are changed?" should be answered before implementing part related tolerances. If materials or manufacturing methods are changed in future projects there will not be any prevailing part related tolerance data available. (Wandebäck och Wahlborg 2015)

Casper Wickman, (Technical Leader at Perceived quality, Volvo Car Corporation) is working with perceived quality and one of the internal customers of the robust design engineers. He was very clear about that part related tolerances should not reduce the flexibility of the development of a car. It must be possible to change designs and still be able to simulate the results. Of course it is good if the work is done more efficient but it should not restrict the freedom of the design. He also raised questions that should be answered before implementing part related tolerances. How similar must concepts be to allow the use of part related tolerances? Different concepts and designs probably have different part related tolerances. Where are the limits of using different tolerances? (Wickman 2015)

The general impression from the interviewees was a curiosity about the possibility of implementing part related tolerances. But most of them also added that it must not limit the design freedom. It should be used to make simulations easier and more precise.

4.4 Suggestions for the function

As described in the beginning of the report the project was initiated to investigate the possibility of using part related tolerances. This would both increase the precision in the simulations and reduce the amount of manual work for the engineers. Today, RD&T supports amplification of variation further away from the reference points, but all tolerances must be applied manually, see Figure 57. The engineers have to look at previous projects and new requirements, and based on that estimate the size of the tolerances. When working with subsystems it is not always possible to apply tolerances to the locating points. This means that the amplification must be calculated manually and applied to each of the measures. When experimenting with the reference system the tolerances must be recalculated and applied several times. This takes a lot of manual work. If RD&T had part related tolerances implemented this could be done automatically. The size of them could also be based on several car models instead of just a few projects that the engineers had time to investigate.

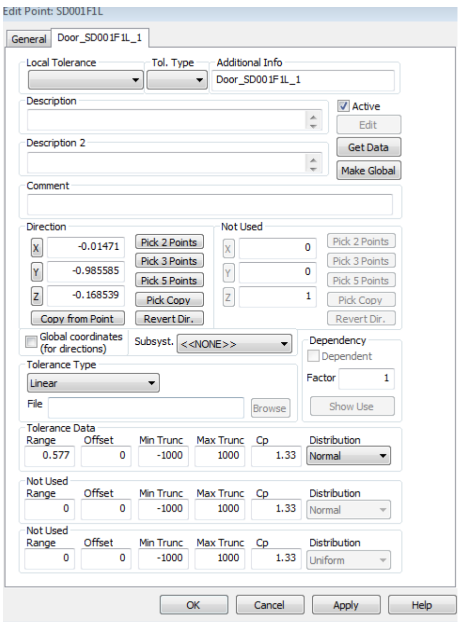

Figure 57 - The "Edit point tolerance" window in RD&T

After talking to the robust design engineers and discussing in the project team the suggestion for implementing the function is as follows. In the part window, shown in Figure 58, a scroll down menu could be added with a list of part related tolerances. For example, “Front door in steel”, “Rear lamp in plastic” or “Bonnet in aluminum” etc. could be possible to choose. By choosing this part related tolerance all points get the right tolerance with respect to the locating system. It would probably also be necessary to choose which type of measure it is. This project showed that gap and flush have different sizes.

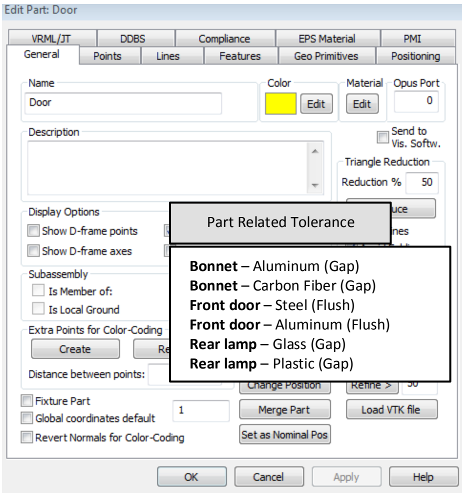

Figure 58 - The "Edit part" window in RD&T

Then, in the tolerance window, shown in Figure 59, the part related tolerance is presented. “Part 1, Front door steel - Part related tolerance, Range: 0.258” is one example of how it could be presented.

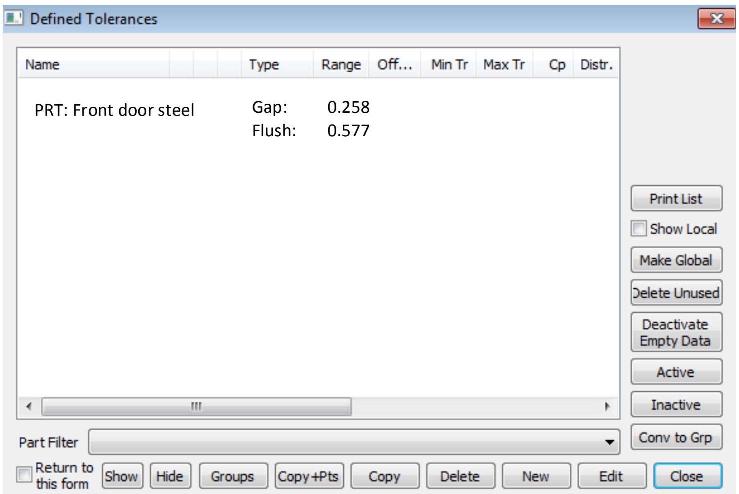

Figure 59 - The "Defined tolerances" window in RD&T

The function could look very different. If the function is to be implemented, one prerequisite is a continued discussion with the users of RD&T but also investigation of more components. This project has studied four components to test the theory. To make the function useful more part related tolerances are needed.

5 Discussion

There might be several factors affecting the results. These factors could be viewed as noise in the system. Some might be related to the measure process. Some might be related to the capability of the simulation. One part of the project was to try to identify some of these factors. To quantify them was not attempted. In this chapter some possible error factors are presented. Furthermore, the results from the different plots are discussed.

5.1 Measure error

When using a CMM for measuring, a probe is sensing the position of different points. It is then possible to calculate the deviation from the nominal value in the vector of the point, i.e. the surface normal. But the CMM does not know where the point is on the part, only where it should be. In Figure 60 the machine is aiming for the cross. The situation to the left is the nominal case. The machine will find the cross in the right position. In the right figure the diagonal line is moved to the right. The machine will then not find the cross but the circle next to it. The horizontal error will be viewed as a deviation in the current surface normal since the wrong point is found. For small angles it does not affect much but for larger angles it would have a larger impact on the result. Therefore the observed error might be larger than the actual error. 3D-scanning would not have this problem since the whole part is identified at the same time.

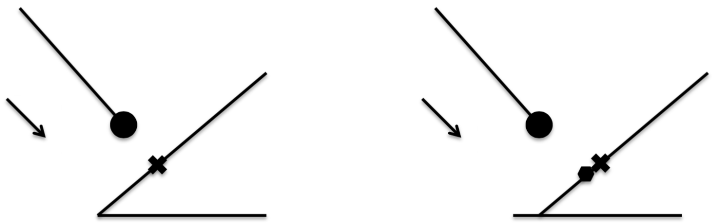

Figure 60 - Measure error with CMM

In order to see the difference between the scan data and the CMM data a small experiment was made. Data about the deviations was gathered both from the scanning process and the CMM process for the XC90 front door. The data was run through the normalization program and then plotted. Figure 61 shows the result. The values are from the XC90 front door. It was not possible to identify the exact same doors and the scan data only had 20 measured doors available. The CMM includes 200 doors. But the graphs still show a large correlation and it can be assumed that the CMM data is fair to use in this project.

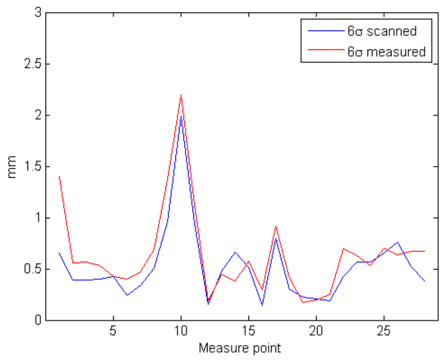

Figure 61 - Comparison between CMM and scan data

The precision of a CMM measuring system, not only the machine, is a couple of tenth of a millimeter (Ohlsson 2015). But it is not possible to give an exact value because the error will grow further away from the original position of the machine. This is due to the construction of the machine. The error is amplified when the arms of the machine are in extended position. Thus it might be different measure errors on different parts of a component.

Fredrik Ohlsson claimed that measuring doors is a safe measuring process. The door is rather rigid and the measurements are trustworthy. (Ohlsson 2015)

5.2 Positioning error

To ease the work for the operators and avoid blocking measuring points the actual reference points are not always used. One example is when measuring doors. The Z reference points are located on the catwalk beneath the window. To position towards these requires that the operator pushes the door upwards in the right position and then closes the fixture at the same time. This is a bad posture from an ergonomic perspective. It would probably also be hard to position it right. Instead the door is placed on two rubber supports and then it can be positioned in X and Y. Then the CMM machine measures the real reference points and recalculates the measures.

In itself the measuring technique works well. What could be a problem is that the supports in rubber could create tensions in the door due to friction, which would affect the shape and, thus, the measure results. In the new XC90 roll bearings are used to avoid this. Some measure data used in this project could however be affected by this.

As presented previously the CMM might not find the reference point but where it should have been. To avoid this measuring of the reference system is iterated a couple of times to come as close as possible to the real reference points.

Previously different Y reference points were used. One set for measuring and another for assembling. Two of the three points were the same. The third point was moved from the lower part to the back arch. Figure 62 illustrates the difference. The right positioning system is more robust since the points are further away from each other. The left one is used for measuring. On the other hand, the part variation is not affected by the positioning system and in this project the simulated doors had a reference system identical to the one used in the measuring. The measures are possible to recalculate between the two systems. There is also a possibility that the door cannot be considered rigid. Then the choice of positioning system would affect. For the newer models the right positioning system is used also for measuring.

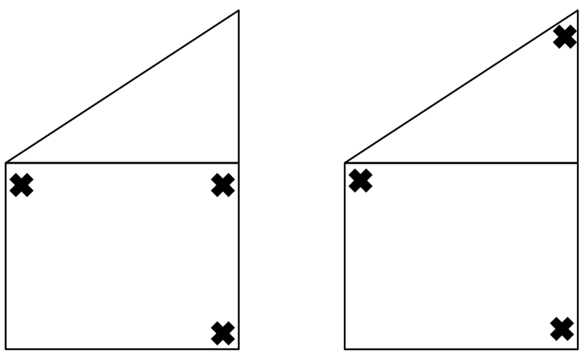

Figure 62 - Different reference systems of a front door

5.3 Cracking

As stated before bonnets and the back arch on the doors are cracked to fit better or reduce the risk for leakage. For the doors it was only a few points that were directly affected by the cracking and in those cases the variation was actually reduced. These points were located on the back arch. When talking to Wandebäck and Wahlborg it was realized that it could be that other points are also affected. When a part of the door is cracked other parts of the door are affected indirectly. This could eventually be observed as strange variations around the door. (Wandebäck och Wahlborg 2015)

Cracking is done because it is cheaper and easier than buying and installing new tools in the factory. If new tools are to be implemented a buffer has to be built and temporary racks must be used because the process must be stopped during the change. A tool change is not very safe either. It requires a lot of trimming before the process is stable. One reason for not buying the right tools from the beginning is that the requirements change over time when more knowledge is gained. Cracking is a stable process within reasonable limits (Ohlsson 2015). However, it is not possible to simulate and of course it is desirable to avoid it.

5.4 Material and manufacturing related errors

There might also be some errors related to the material and manufacturing process. When manufacturing a bonnet for example, two sheet metal parts are joined together. Then there will be one corner where the parts do not fit very well to each other. Fredrik Ohlsson described it as closing a lunch box (Ohlsson 2015). One corner will be harder than the others. It is hard to predict how that corner behaves. Usually, it is chosen to be one of the corners close to the windshield because it is not as visible there as in the front. Also in this corner a reference point in Z is located. This could affect the positioning of the bonnet negatively.

Another problem in manufacturing is that many components, including the bonnet and the doors, consist of an outer and an inner part, which are not easy to fit together. A box is easy to place in a corner but not in a bowl. The inner part of the component should be placed on the outer part and the edges are folded. This process is similar to placing a bowl in another bowl. It is hard to determine how it should be placed to fit the requirements. Further, the glue is not dry when the component is moved and it could be that the structure changes slightly.

Wandebäck and Wahlborg discussed the possibility that where on the coil the sheet metal has been, also affect the deviations. They said that if the sheet is on the outer part or inner part of the coil could result in different residual stresses in the material (Wandebäck och Wahlborg 2015). This might be true, but Dag Johansson claimed that the sheets are rolled in a way that the stresses are neutralized (Johansson 2015). However, this could be worth confirming when studying the causes further. Wandebäck and Wahlborg also said that the parts are cut in different directions to maximize the number of parts from each square meter of sheet metal. (Wandebäck och Wahlborg 2015) If the residual stresses in the material are not neutralized the components would behave differently depending on their direction.

Temperature variation does probably not have a very large impact on the measuring (Ohlsson 2015). The measure room always has approximately the same temperature and the fixtures are not used until they have the same temperature as the room. This is probably not a large contributing factor.

5.5 Simulation

The simulations were performed with the software RD&T. It uses Monte Carlo simulation for predicting the variation. The results are more or less normally distributed. In reality, changes in the process affect the results meaning that the output of the measure data is not normally distributed over time. The mean and standard deviations usually change over time. This was the main reason for making it hard to find measure data that was possible to compare with the simulated data. Changes are hard to predict and simulations have a limited possibility of correlating with the real process.

Gap and flush were handled separately because the best fit should be as good as possible without disturbance from the other type of measures. They were also presented separately because they are different types of measures with different sizes. For a couple of components one reference point had to be locked when making a best fit because there were no measure data in that direction which did not make it possible to find an optimal position. For example, the flush measures on one of the doors only had vectors in Y and Z. Then it was not possible to make a best fit in X, and it was locked. It could have been better to make the best fit with all measures and then present them separately (Lindau 2015). Björn Lindau also raised the question if the vectors are changed when making a best fit. If not, the surface normals would be the same as before but the points would have moved and the "shape" of the component would not be the same (Lindau 2015). Figure 63 shows that when rotating the object the vector remains the same.

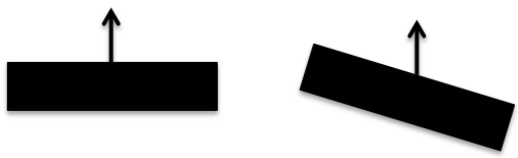

Figure 63 - Vector remaining the same when an object is rotated

It was discovered during the project that the simulated data was not affected much by changing the tolerance within reasonable limits. Using the tolerance of a component, a part specific tolerance, or the mean of all models of that component, a part related tolerance, did not seem to change the output much. The simulated plot was moved a couple of tenth of a millimeter and amplified very little. Therefore it did not matter which of these tolerances that were used in this study. It is more important when trying to quantify the part related tolerance, which was out of the scope of this project.

5.6 Compliancy

The part related tolerance for the bonnets showed no indication of correlation between the simulated and measured data for the small sample method. In the large sample plots there were more correlation but the simulated and measured curves did not have the exact same shape. There are several reasons for why this is. One could be that the bonnet is a non-rigid part but it was simulated as a rigid part. In the simulations in RD&T the bonnet was simulated with the four Z-points, using alternative assembly. The alternative assembly mirrors the positioning fixture better than only using the single 3-2-1 system and resulted in calmer 6σ plots. Positioning the bonnet with four Z-points is a robust system and it is therefore RD&T returns these results. In the large sample method the simulated and the measured curves looked more alike than for the small samples, but there are still some deviation between them that also can be explained by the lack of compliancy in the simulation.

Flush measures of the bonnet are more sensitive to the compliancy problem than gap measures. This is because the bonnet deforms in the same direction as the flush is measured. This can result in larger flush values.

The investigation revealed that for some doors it was more difficult to find a correlation between the measured and the simulated curves. This resulted in an analysis of the different designs of the doors, presented further down in this chapter. Some doors have features on them that might help the sheet metal to become less likely to deform explaining the fact that some doors are easier to predict.

5.7 Human error

"As with other methodologies, application of capability studies is not without problems. Often there is a gap in industry between how such studies should be performed in theory and how they are applied in practice." (Bergman & Klefsjö 2010) As there are many people involved in the controlling of a process, there is maybe not a common understanding of what it is used for. Quality management and capability studies are important in order to secure a process that delivers products that fulfills its intended purpose. If there is someone in the process that fails to recognize this faulty data might be delivered. Casper Wickman pointed out that most often the task of controlling the process is considered redundant and something that just needs to be done and might not be done in a careful manner (Wickman 2015). The state of the operator is important as this is a factor of how the measuring will be done, maybe the operator might do the task differently on a Monday morning than on a Friday afternoon (Wickman 2015). "But the most frequently stated difficulty is related to a lack of knowledge and commitment from top management, and to insufficient resources for capability studies and utilization" (Bergman & Klefsjö 2010). Bergman and Klefsjö also stress the fact that capability studies might single out an operator as a cause for an error in the process, which might generate fear for the operator to deliver faulty data (Bergman & Klefsjö 2010). Data might be "corrected" to be within its specified limits. Peter Edholm said that it is common that data from suppliers might be polished in order to look good (Edholm 2015). Data outside the tolerance limits can indicate that the process is not under control. It is an easy fix to change the data rather than to change the process. It is easier to do business as a supplier if the process that one offers is under control.

In a visit to VCBC where the manufacturing and measuring of VCC's body components is carried out, reasons for error were discussed with Fredrik Ohlsson. He expressed that at VCBC they work in three shifts with measuring components and it is not easy for every operator to know what has happened since the last shift (Ohlsson 2015). A fixture might have been transported to a different location and then be transported back for more positioning at VCBC. During transportation the fixture may be subject to vibrations and poor handling, which can change its setting. The fixture could also have been stored outside where the temperature is lower than inside, which make its material compress due to thermal shrinkage. The operator is often unaware of all the things that happens to the fixture and might be a reason for why the measured data does not correlate with the simulated data. Fredrik Ohlsson also said that the tolerances that VCBC receives from VCC sometimes are not valid later in the development process (Ohlsson 2015). Often VCBC receives tolerances in an early development phase and develop the manufacturing program to work for these. When the car is later being produced VCC asks for new tolerances as gap, flush or parallelism relations are not looking good. As all equipment has been bought and tuned to work for the early tolerances other methods must be used to achieve the new tolerances. The new methods are for example the cracking of the upper part of the doors and the cracking of hoods. These types of manufacturing methods are hard to simulate in RD&T.

The capability studies at VCC are heavily automated which also will generate human errors. There are three concerns with automation: loss of skills, inappropriate trust and out of the loop performance problems (Bligård 2014). Loss of skills stresses the problem that the operator might lose knowledge and skills of what is to be performed and therefore might not understand what is done. If the operator does not understand what is done it is very difficult for this individual to know when faulty data has been measured. The second problem with automation, inappropriate trust, is that the operator puts too much trust into what the machine does and disregards the fact that the machine might be performing poorly. In the case of the capability studies at VCC the CMM machine might be delivering faulty data if its performance is lacking. This combined with loss of skills problem will lead to data that is incorrect. The third problem with automation, the out of the loop, highlights the fact that the operator gets left out of the process. Which leads to the irony of automation formulated by Bainbridge: “The higher the level of automation that is created, the more dependent you become on the few people left ’in the system’ to manage the tasks that for some reason could not be automated.” (Bainbridge 1983). What could not be automated, that is difficult and seldom occurring tasks, is assigned to the few operators left in the process, which leads to high belief in human capabilities. Workloads can become very high at certain occasions, often during malfunctions. Important to know is that human errors are not removed with automation it is just moved to the engineer or the programmer of the automation system (Bligård 2014).

The fact that the authors of this master’s thesis are also human cannot be disregarded. The method included a lot of manual work in RD&T and some minor errors might have been performed. Much attention was put on checking the simulations several times and correcting the method in order to achieve believable data.

5.8 Quality of sample data

The quality of the sample data was investigated to determine if that could affect the results. This was made after the small sample results were found. Previously, the function “Cluster reduction” in RD&T had been used to identify points that act similarly in the measure data. Unfortunately, it did not give much that could be used and the work was canceled. In this next phase the V70 rear door, which already had a pretty good correlation, was studied at first. Then the V70 rear lamp, which did not have a clear correlation, was studied.

The measure data was transformed into numbers with Matlab and imported into the software Minitab. Minitab is a statistical tool, which easily plots histograms and normal probability plots, and other statistical analysis tools. Also the simulation data was analyzed. The results from the work can be found in Appendix 6. It is clear that the measure data has a weak quality in both cases. In other words, it is far from normally distributed. Minitab also returned p-values for each measure point. Many of the measure points gave small p-values stating that the null hypothesis is untrue. In other words there is a high chance that the next set of data will not fall within the sample range. The samples are not normally distributed. This means that the data cannot really be trusted or compared with the simulated data.

The balance between finding a large sample and a sample without mean shifts was hard. Therefore Kristina Wärmefjord was consulted (Wärmefjord 2015). She explained how the mean shifts could be handled. This resulted in the work with analyzing larger samples and to calculate the standard deviation in small steps. That made the measure data more trustful. Some of the plots became more aligned after this step.

5.9 Analysis of design

After the results had been gathered it was decided to analyze the designs of the doors and the bonnets. This was done in order to map why they behave the way that they do. An evaluation sheet of the front and rear doors and the bonnets can be seen in Appendix 7. The conclusion that can be drawn from the investigation is that features on doors make them more rigid, as the sheet metal is subject to a lot of treatment. This can be explained as: Imagine a clean piece of paper, which in this state behaves non-rigid and when folding the paper it will make it more rigid. When the doors are rigid they show a trend of less variation and helps explain why the plots for the XC60 front and rear door are subdued. The V70 rear door does also have a feature, which gives the simulated curve and the measured curve a close resemblance.

Another reason for the calm behavior of the XC60 and V70 plots is that these doors include a plastic feature at the bottom of the door. Gap and flush measures are for this cause not performed on the bottom of these doors. Instead the attachment holes for the plastic part are measured. The bottom part of the door is far from the reference points and prone to amplification of the variation. If these parts are not measured it is then easy to explain why the curves behave calmer for these doors.

The rear door of the S60 has a different back arc than the other doors that has been investigated. The S60 back arc has a circular form compared to the square shape of the other doors back arc. As it is the points on the back arc of the S60 that deviates from the simulated curve it might explain why the curve behaves as it does.

The bonnets do not show an obvious correlation between the plots and the design. What can be said about the bonnets, but also the doors, is that the gap shows more correlation than the flush. That is logical because the flush is more coupled with the compliancy of the components.

5.10 The promising results

This chapter has presented much that could have gone wrong. However, some results were promising.

At first the bonnets showed results that would probably not be able to use, but after the larger samples were implemented the gap plots were aligned. This means that the gap would probably be able to anticipate through simulations of bonnets.

For the doors the simulation results were also promising. Especially the gap plots showed curves that were close to each other. The results from the V40, V70 and XC60 rear doors and the XC60 front door were positive. For the flush measures a correlation could be identified but the curves were offset and generally the measured data was more amplified than the simulated.

In the case with the rear lamps the XC60 displayed a correlation for both flush and gap. The V70 evinced exceptional result for gap.

Concluding, there are results that indicate that part related tolerances could be used for the kind of components that has been investigated.

5.11 Applicability on new concepts

This project was aimed at identifying a correlation between measured and simulated data for some components. The studied components have been of the same shape and material. One thing that would be interesting to look into is how components and their variation are affected when materials or processes are changed. It is not good to use a part related tolerance if it can only be applied on a future component with the same shape and material. Designers must be able to try new ideas and not be too limited by old work procedures. Casper Wickman said that it is a balance between working efficiently and flexibly (Wickman 2015).

The part related tolerance might at least give a hint about the size of the variation. In this project the found part related tolerances for each model were about the same size. Different components had different part related tolerances and that was expected, but all models had similar tolerances for each component. Hence, the probability that new concepts would have the same tolerance as the previous is rather high, at least if it has similar shape, material and process.

6 Conclusions

This chapter is a final statement from the authors taking into account all the other chapters. The chapter aims to answer the question: “Is it possible to use part related tolerances?” that this master’s thesis is founded on. It also includes how to proceed with the result that has been gathered.

In Appendix 8 all the conclusions that have been gathered during the project is presented along with comments that speak both for and against them.

6.1 Measuring

During the project it was realized that the CMM does not find the actual points, but where it should have been. In the end this was compared with the scan data where the whole component is measured simultaneously, reducing this effect. The comparison showed that the deviation between the two ways of measuring is not large. It could also be due to different samples. Concluding, the data from the CMM is trustworthy based on this investigation and can be used for the purpose of this project.

6.2 Sample

It became clear as the project progressed that the large samples had too many mean shifts and the small samples were not representative for the actual variation. When the large samples were treated with the new method of normalization the results became promising. Previously, when small samples were used the choice of measure data was of high importance for finding a correlation, at least for the bonnets and the rear lamps. But when the larger samples were normalized the output did not seem to change much regardless of what sample was used. On the other hand it turned out to be necessary to use large samples for some components only. But it would not change the results for the worse when using large samples for all components.

The size of the window when calculating the standard deviations did not matter much. The results turned out to be almost the same. Also the choice of number of iterations for removing values outside the control limits did not affect the results much. One iteration was enough for identifying a correlation in this project.

6.3 Design analysis

The investigation of different designs on the doors and bonnets yielded some information that can be used as conclusions for the results seen in the different plots. First, features on doors, such as catwalks, seem to make the doors stiffer. The stiffness helps to make the doors vary less and makes their manufacturing more stable. This is backed up by the plots in the results as the doors that did not have features on them showed simulated and measured curves that did not correlate, but the doors that had features on them showed more correlation. However, the doors that showed correlation, the XC60 and V70, did also have a plastic part assembled to the bottom of them. This plastic part makes it unnecessary to measure gap and flush on the bottom of these doors, which is unfortunate because on the other doors this area was the one that showed the most variation.

If the doors lack features it makes them more prone to deform and should maybe be simulated compliant instead of rigid. This would mirror the actual behavior of these specific doors more. The bonnets did not show a clear connection between the plots and the designs. The V40 and the XC60 showed promising results and the XC90 did not correlate as much. This was strange because the XC90 is not cracked. The good results could be due to more stiffness in the V40 and XC60 because of design or cracking, but this is not confirmed.

The design of the fixtures is also important for how the output from simulations will be. It turned out that a small triangle created by the A-points resulted in less measuring errors and the simulated and the measured curves behaved more alike. This is because RD&T evaluates the design of the locating scheme and nothing else. If the locating scheme is robust, RD&T will deliver variation that is small. But in reality there are a lot of things that can affect the outcome when measuring a part, and sometimes RD&T and the actual measuring can show two different things.

6.4 Materials and manufacturing

The first conclusion on materials and manufacturing is that the manufacturing process is hard to simulate. The world is full of variation and to simulate it with a part related tolerances might be difficult. There are many noise factors affecting the manufacturing and measuring and to consider all is not possible. Cracking is one typical process step that is hard to simulate. Cracking is a frequently used method and makes the simulations and the manufactured components generating different distributions.

Changing materials would probably also change the behavior of the components and hence the variation. Using part related tolerances would therefore be limiting if the materials are changed. But it has not been confirmed in this master's thesis.

6.5 Part related tolerance

When studying the plots, gap values were generally more aligned than for the flush values. It would probably be possible to use a part related tolerance for most components when studying gap. To draw a general conclusion that part related tolerances could be used is more difficult. The answer is probably yes but this must be further investigated to be able to make a more confident statement. More components should be studied and eventually it is necessary to have many part related tolerances on different parts of a component. For example, it would be possible to have one tolerance for flush on the back arch and another for the bottom part of the door. This would increase the precision. Probably it would also be necessary to make the part related tolerances design specific.

The exact size of the part related tolerance was of low importance for this project. The curve was just offset and slightly amplified. To find a correlation, the size of the value on the part related tolerance did not matter.

Applicability on new concepts was hard to determine. In this project three to five models were tested and all were rather similar. Probably, future concepts would have a design close to the previous but there is no guarantee that the part related tolerance would work on those as well.

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8 Appendices

Appendix 1: Gantt-schedule

Appendix 2: Developing the method

This chapter contains the initial method and results of it, that lead up to the understanding of the problem and how it should be tackled. Thus it developed the final method that should be used to find part related tolerances.

Creating prerequisites

In this project the part variation was studied. The positioning variation had to be eliminated since the influence of it might amplify the variation. It was first investigated if there was any possibility to use 3D-scanning. Soon it was realized that it might be hard to get a large set of data over time and it was decided to instead study already measured components. However this data was gathered with the parts in a fixture, meaning that the output would not only be part variation, but both part and positioning variation.

To handle this it was realized that making a best fit would lower the influence of the positioning and only the part variation could be studied. One way to do this was making a Matlab-script for it. After some time it was realized that RD&T already had a best fit function. It adjusted the reference points with an offset with respect to the other points of the part using the least square method. It means that the distance from the measured values to the nominal values become more similar instead of having some very large and some very small.

There was a problem with the function. It first calculated the mean for each point and then made a best fit. In this context it could not be used since each measured component had to be positioned with best fit individually. It would then be possible to generate an offset for each reference point on each measured component. Using the 3-2-1 positioning system and having for example 100 components would generate 600 offsets. Lars Lindkvist, the examiner of this master's thesis and also the developer of RD&T, understood the problem and soon he added a new function to RD&T that solved the problem with the best fit. The new functionality made this individual best fit instead of taking the mean of all components. But before this was implemented fully functional it was possible to take one component at the time, because the mean of one component is the actual value. Since a statistical ground was needed for drawing any conclusions it was necessary to study a lot of samples of each component.

The information given as offsets could be plotted using the software Matlab to see the deviations and means of the components. Also, the standard deviation was calculated for each point. The mean of all standard deviations multiplied by six (which is the 6σ value used for non-critical components) was used as a range of the tolerances in the final simulations. These final simulations were then compared with the measured data from CM4D to identify a correlation.

Small samples of bonnets

Before the new best fit function was fully functional the old one could be used but for one sample at the time. After discussion with the supervisor, Dag Johansson, it was decided to first study the outside of the bonnet of a Volvo XC60. Only the gap and flush relations were studied. To make the best fit as good as possible the edge points and the surface points were studied separately. The surface points were called A-points and the edge points were called B-points.

From CM4D it was possible to export the feature grid (the nominal grid of points, including coordinates and vectors of each point, measured in the process) and the data grid (the deviations in each point for each sample). This could then be imported into RD&T that created a raster of points with one offset in the first case when looking only on one sample. (In the next step it included a set of offsets, one for each sample.) As soon as the geometry was defined the reference system could be defined. The same reference points as for the real bonnet were used. This can be seen in Figure 64.

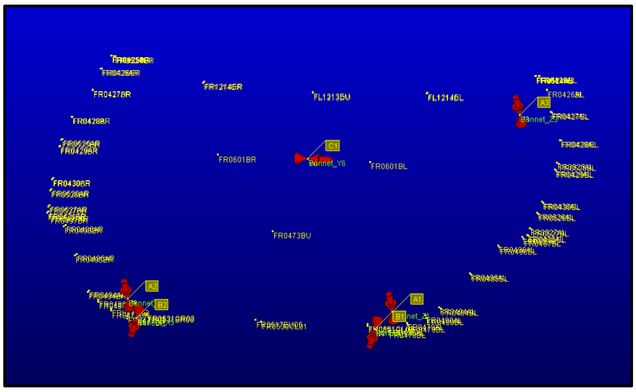


Figure 64 - Data- and feature grid for the XC60 bonnet

When making a best fit of each bonnet the deviations (in the Figure 65 below presented as mean because there is only one bonnet) of each point became more similar. This is logical due to the theory of the least square method.

Measure	Range	6 Sigma	8 Sigma	Mean	Mean shift
Bonnet_FR0426AR.N	0	0	0	-2.32	-2.32
Bonnet_FR0425AR.N	0	0	0	-2.19	-2.19
Bonnet_FR0525AR.N	0	0	0	-2.03	-2.03
Bonnet_FR0431AL.N	0	0	0	-1.98	-1.98
Bonnet_FR0428AR.N	0	0	0	-1.94	-1.94
Bonnet_FR0429AR.N	0	0	0	-1.88	-1.88
Bonnet_FR0497AL.N	0	0	0	-1.76	-1.76
Bonnet_FR0527AL.N	0	0	0	-1.76	-1.76
Bonnet_FR0524AR.N	0	0	0	-1.65	-1.65
Bonnet_FR0430AL.N	0	0	0	-1.55	-1.55
Bonnet_FR0430AR.N	0	0	0	-1.55	-1.55
Bonnet_FR0526AL.N	0	0	0	-1.54	-1.54
Bonnet_FR0429AL.N	0	0	0	-1.35	-1.35
Bonnet_FR0525AL.N	0	0	0	-1.31	-1.31
Bonnet_FR0426AL.N	0	0	0	-1.31	-1.31
Bonnet_FR0425AL.N	0	0	0	-1.3	-1.3
Bonnet_FR0526AR.N	0	0	0	-1.25	-1.25
Bonnet_FR0496AL.N	0	0	0	-1.19	-1.19
Bonnet_FR0431AR.N	0	0	0	-1.11	-1.11
Bonnet_FR0427AR.N	0	0	0	-1	-1
Bonnet_FR0527AR.N	0	0	0	-0.97	-0.97
Bonnet_FR0495AL.N	0	0	0	-0.78	-0.78
Bonnet_FR0428AL.N	0	0	0	-0.75	-0.75
Bonnet_FR0524AL.N	0	0	0	-0.75	-0.75
Bonnet_FR0497AR.N	0	0	0	-0.73	-0.73
Bonnet_FR0480AL.N	0	0	0	-0.54	-0.54
Bonnet_FR0479AL.N	0	0	0	-0.46	-0.46
Bonnet_FR0494AL.N	0	0	0	-0.38	-0.38
Bonnet_FR0478AL.N	0	0	0	-0.26	-0.26
Bonnet_FR0427AL.N	0	0	0	-0.21	-0.21
Bonnet_FR0480AR.N	0	0	0	-0.12	-0.12
Bonnet_FR0479AR.N	0	0	0	0.06	0.06
Bonnet_FR0496AR.N	0	0	0	0.18	0.18
Bonnet_FR0478AR.N	0	0	0	0.18	0.18
Bonnet_FR0494AR.N	0	0	0	0.47	0.47
Bonnet_FR0495AR.N	0	0	0	1.06	1.06

Measure	Range	6 Sigma	8 Sigma	Mean	Mean shift
Bonnet_FR04...	0	0	0	-0.973	-0.973
Bonnet_FR04...	0	0	0	-0.962	-0.962
Bonnet_FR04...	0	0	0	-0.793	-0.793
Bonnet_FR05...	0	0	0	-0.735	-0.735
Bonnet_FR04...	0	0	0	-0.672	-0.672
Bonnet_FR04...	0	0	0	-0.66	-0.66
Bonnet_FR04...	0	0	0	-0.649	-0.649
Bonnet_FR04...	0	0	0	-0.6	-0.6
Bonnet_FR05...	0	0	0	-0.55	-0.55
Bonnet_FR04...	0	0	0	-0.539	-0.539
Bonnet_FR05...	0	0	0	-0.442	-0.442
Bonnet_FR04...	0	0	0	-0.376	-0.376
Bonnet_FR05...	0	0	0	-0.311	-0.311
Bonnet_FR05...	0	0	0	-0.276	-0.276
Bonnet_FR04...	0	0	0	-0.255	-0.255
Bonnet_FR04...	0	0	0	-0.197	-0.197
Bonnet_FR04...	0	0	0	-0.144	-0.144
Bonnet_FR04...	0	0	0	-0.126	-0.126
Bonnet_FR04...	0	0	0	-0.126	-0.126
Bonnet_FR04...	0	0	0	-0.0879	-0.0879
Bonnet_FR04...	0	0	0	-0.0774	-0.0774
Bonnet_FR04...	0	0	0	-0.0703	-0.0703
Bonnet_FR04...	0	0	0	0.0195	0.0195
Bonnet_FR04...	0	0	0	0.0457	0.0457
Bonnet_FR05...	0	0	0	0.084	0.084
Bonnet_FR04...	0	0	0	0.137	0.137
Bonnet_FR05...	0	0	0	0.382	0.382
Bonnet_FR04...	0	0	0	0.399	0.399
Bonnet_FR04...	0	0	0	0.557	0.557
Bonnet_FR04...	0	0	0	0.722	0.722
Bonnet_FR04...	0	0	0	0.739	0.739
Bonnet_FR04...	0	0	0	0.744	0.744
Bonnet_FR04...	0	0	0	0.785	0.785
Bonnet_FR05...	0	0	0	0.988	0.988
Bonnet_FR04...	0	0	0	1.03	1.03
Bonnet_FR04...	0	0	0	1.71	1.71

Figure 65 – Before (left) and after (right) best fit

The software calculated the offsets but due to a bug they had to be applied to the reference points manually together with the vectors. This was rather time consuming and only 20 bonnets were investigated in this first step. When the reference points had their new position in the best fit situation it was possible to do a variation simulation with one iteration to calculate the position of all other points. These were exported to Matlab and plotted to illustrate the deviations. Also the standard deviation and the mean for each point were calculated. Figure 66 and Figure 67 below show the results of the simulations.

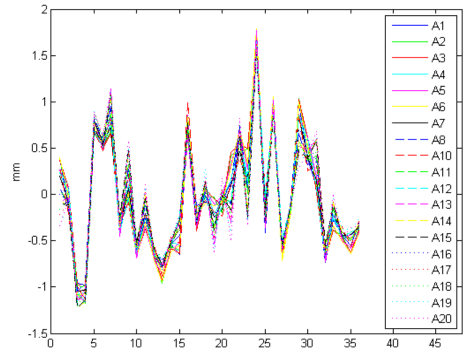


Figure 66 - Deviation from the nominal for flush on each bonnet

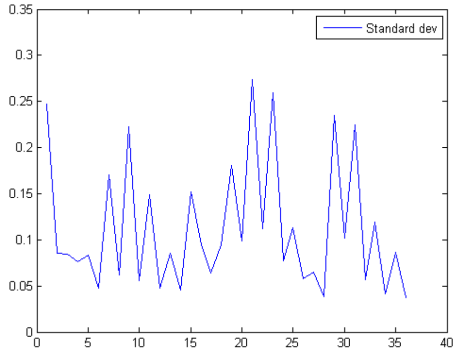


Figure 67 - The standard deviation in each flush point

The X-axis presents the different points and the Y-axis presents the level in millimeters. The shape of the curve itself is not of much value. It is the levels of the nodes that are important. To use points could have been better to not mislead to think about it as a graph but it would be much harder to interpret.

As we can see the curves follow each other fairly well meaning that the bonnets behave similarly. The variation is not only random. Some points are above nominal and some are below nominal, both for the surface points. As stated above the standard deviation was also calculated for each point. This is illustrated in the figure above. The mean of this was calculated and multiplied by six to the 6σ value. For 20 bonnets it was 0.6741 for the surface points and 0.8052 for the edge points. This was applied as a range to all points in the RD&T model. Now all other tolerances except this range were set to 0. This would generate the mean part variation. This was called final simulation, but only for each part. Doing a variation simulation of this model with the new tolerances generated a set of simulated data that was plotted together with the measured data from CM4D. If they correlated it could be said that it might be possible to use a standard tolerance for simulating the part variation. If the difference would be close to 0 or at least around the same level in all points it would be possible to simulate the real part variation well. As shown in Figure 68 and Figure 69, 20 bonnets seem to be a too small sample to allow drawing conclusions. There is not much correlation.

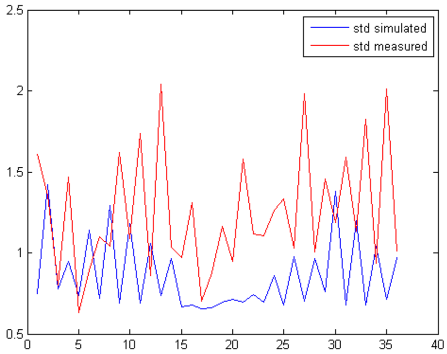


Figure 68 - Flush for simulated and measured data

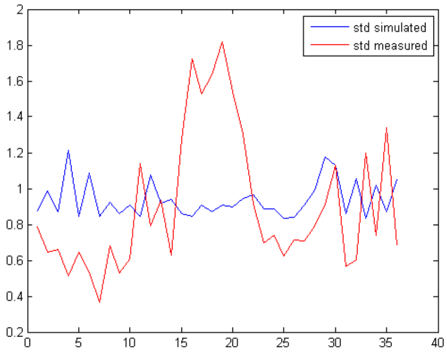


Figure 69 - Gap for simulated and measured data

Especially in the upper figure but also in the lower it looks like there is a negative correlation. When the measured standard deviation is high the simulated is low and vice versa. It is hard to say why this occurs. If the difference would be close to zero it could be said that it is possible to simulate the outcome well. The plots above do not support the correlation. However, there seem to be a small correlation in the lower plot between points 20 and 30. The edge points do not have as large deviations as the surface points.

Larger samples of bonnets

When the simulations of the small samples were made and the new best fit function of RD&T had been implemented which could handle more than one sample at a time, larger samples was used. At first 100 bonnets were tested and after that 500 bonnets. These simulations show the same pattern and only the ones with 500 bonnets are presented below. Later on it was realized that 500 samples does not only mean positive effects on the results. It could also mean that changes in the process that might influence the results have been made. Therefore smaller samples that were checked to be normally distributed were used in the continued project.

Just as in the case with one bonnet at the time the work with many bonnets started with importing a feature grid into RD&T. The locating scheme was defined based on the real one. Now the data grid included 500 samples with the deviations in each point respectively. This was imported as tolerances to the points of the model. The new best fit function, called “Single Opt”, was used to evaluate the model. What it did was calculating the least square of the deviations in all points of each measure occasion and adjusting the reference points to locate the part in a best fit position for each sample. 500 bonnets needed 500 iterations of best fit and this generated 500 offsets for each reference point. Now there were 500 best fit positioned bonnets.

First a variation simulation was made with the tolerances based on the measure data. This required 500 iterations, one for each bonnet. This could be done without further changes since all points already had a lot of data from CM4D. The result is shown in Figure 70 and Figure 71.

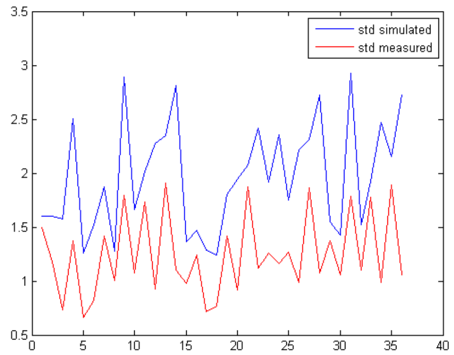


Figure 70 - Flush for simulated and measured data

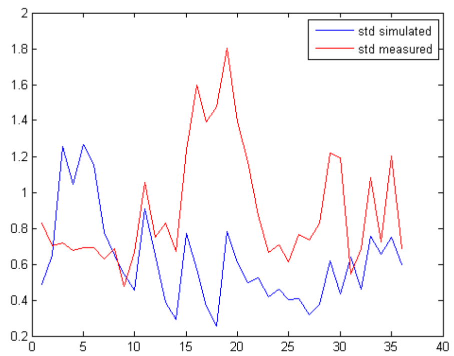


Figure 71 - Gap for simulated and measured data

There seem to be some small correlation between the simulated data and the measured data. However, this was with the tolerances based on the measured data in each point. Obviously the simulated data will follow the measured data. When working with a specific part, like the XC60 bonnet in this case, it might be useful, but when trying to apply the data to the next generation parts problems might occur. First, there is no measure data of the new parts in the early project. Second, the data from inspected points is not simply transferrable to the new components. If that was the case it could be done already today. When making a best fit the deviations in all points become more similar. The large ones become smaller and the small ones become larger. If it would be possible to make a perfect best fit all deviations would be the same. It could be assumed that it is possible to calculate mean of all standard deviations in each point.

With a variation simulation it was possible to calculate the standard deviation. The mean of all these deviations, one for each point, was calculated and inserted as a new tolerance to all points. The vectors were the same as before, given by the feature grid, but the range was set to the mean in all points and the offset was set to zero. The measure data was not used in this step. A variation analysis was made and the result of the standard deviation is shown in Figure 72 and Figure 73 below.

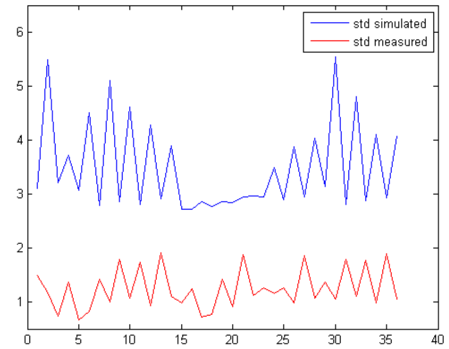


Figure 72 - Flush for simulated and measured data, with a mean standard deviation

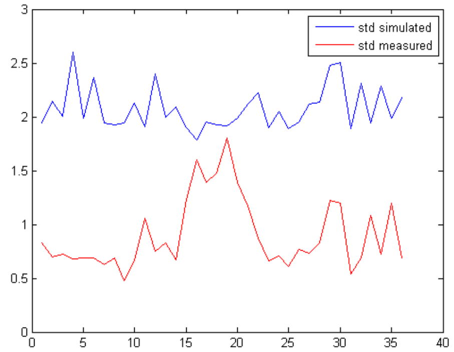


Figure 73 - Gap for simulated and measured data, with a mean standard deviation

Again, there seem to be a negative correlation, even though a large sample was used. One explanation might be that the bonnet is far from rigid and support points are used for supporting the fourth corner in z-direction. In the simulations the bonnet was considered rigid and only the main locating system, 3-2-1, could be used. This might affect the results.

Another thing that could influence is cracking. This is a technique for making the bonnet fit better. This could be a reason for finding just a vague correlation between the simulated and measured data. After discussions with Dag Johansson it was realized that probably the measurement error would be more visible for this type of part. It was decided to look on a left front door of a Volvo V40 instead, which uses an easier positioning system.

Left front door of V40

The reason for choosing a left front door was that the deviations might be a bit larger and the measurement error would not be as large as for the bonnet. This would make it easier to identify a possible correlation. As already said, the chosen door was from a Volvo V40.

The procedure for working with the door was the same as for working with the 500 bonnets. A feature grid was imported and the reference system was defined. The data grid included 500 samples but only 126 of these included valid data. When making the best fit 500 iterations were made but for the variation analysis later on, only 126 iterations were needed. The results are shown in Figure 74 and Figure 75.

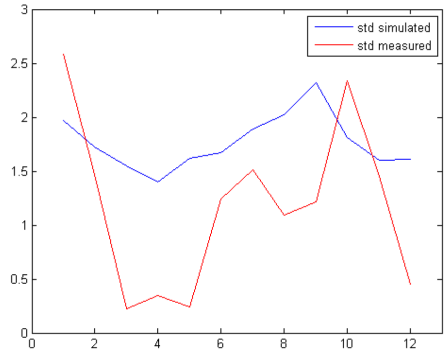


Figure 74 - Flush for measured and simulated data

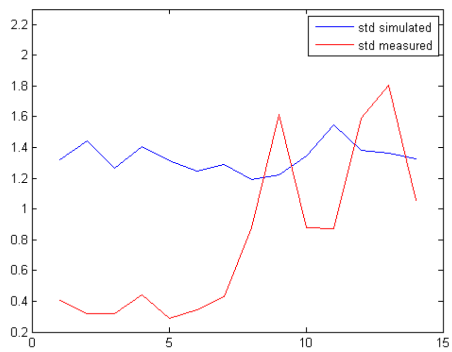


Figure 75 - Gap for simulated and measured data

Here the plotted curves follow each other more than for the bonnet, at least the flush. One thing to notice is that for points seven to nine in the flush, the measured data has lower variation. These points are located at the back arch that is cracked. This is because driving fast results in lower pressure outside the car that might cause leakage or noise if the door does not retain. After the treatment the variation is reduced locally. The other points follow a logic pattern with larger variation further away from the reference points.

Left front door verification

To be able to draw any conclusions about the possibility of using part related tolerances the found results had to be tested on other types of components. The tolerances of the V40 door were used in simulations of doors of several other door types, more specifically XC90, XC60 and V70. At least for the XC90 the result was promising; see Figure 76 and Figure 77.

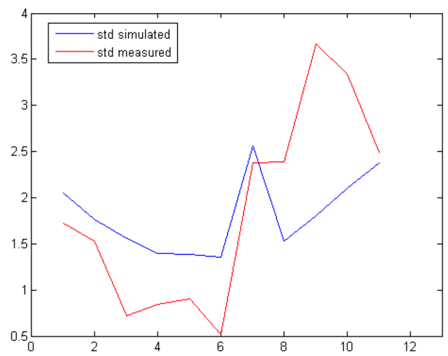


Figure 76 – Flush for simulated and measured data using V40 tolerance on the XC90

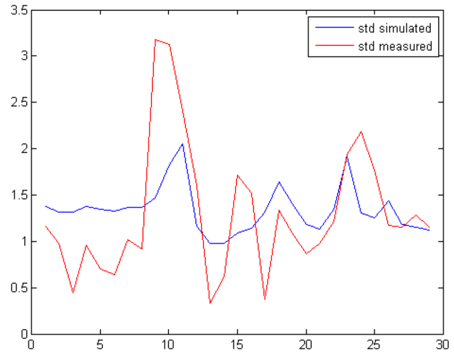


Figure 77 - Gap for simulated and measured data using V40 tolerance on the XC90

It is clear that there is some connection between the measured data and the simulated. Also the other tested models showed an interrelation between the curves but with some offset. The curves had a similar shape, meaning that the door behaves similarly in manufacturing and in simulations. The results this far suggested that for some parts it would be hard to find a relation between the simulated and the measured data, like the bonnet, and for some parts it would be more plausible, like the door.

To refine the simulation even more the measured data was studied in more detail. It was realized that changes in the process affect the results of the measuring. When looking at the results of the measured data over time it was clear that some sections was not normally distributed. In order to find the part variation without assignable causes of variation it was necessary to sort out the obvious "leaps", see Figure 78.

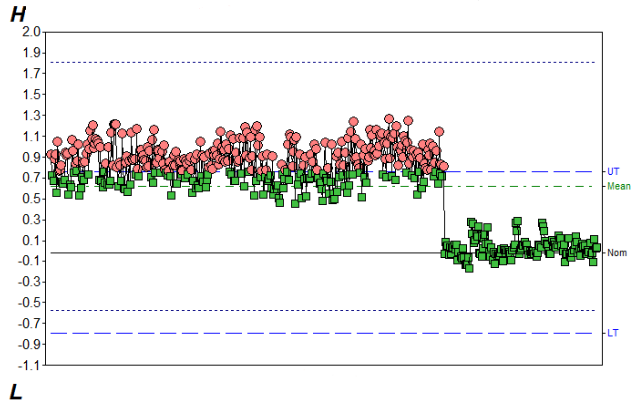


Figure 78 - Mean shift due to removal of an assignable cause in the process

Together with Dag Johansson it was decided that measures from a period of one to two months without "leaps" would be most useful. It would result in around 20 measure occasions for each component. This would then lower the standard deviation.

Further, it was realized that using a part related tolerance from only one car model would not be as good as taking the mean from many different models. Therefore the best fit and analyzing of part related tolerances were made for several models. Then the mean was calculated and again verified by plotting the results together with the measured data directly from CM4D.

Appendix 3: Matlab code

Code for step-wise calculating of standard deviation and plotting

```
clear all
close all
clc

filename_sim = 'V40Gap.txt';
filename_mea = 'DataGrid.csv';
a='V40 Gap';
%% Open the datagrid file and convert to a matrix
delimiter=char(','); % Where to create a new cell
fid = fopen(filename_mea,'r');   %# Open the file

  datagrid_string = cell(10000,1);     %# Preallocate memory
  lineIndex = 1;                  %# Index of cell to place the next line in
  nextLine = fgetl(fid);           %# Read the first line from the file, fgetl
reads the next line in the file
  nextLine = fgetl(fid);          %# Read the second line from the file
  nextLine = fgetl(fid);

  while ~isequal(nextLine,-1)          %# Loop while not at the end of the
file, which -1 indicates
    datagrid_string{lineIndex} = nextLine;   %# Add the line to the cell
array
    lineIndex = lineIndex+1;          %# Increment the line index, to go to
the next line in the matrix 'featgrid'
    nextLine = fgetl(fid);            %# Read the next line from the file
  end

  fclose(fid);                    %# Close the file
  datagrid_string = datagrid_string(1:lineIndex-1);  %# Remove empty cells,
if needed

  % Now it is time to sort the data into columns

  for iLine = 1:lineIndex-1                %# Loop over lines
    lineData = textscan(datagrid_string{iLine},'%s',...  %# Read strings
                        'Delimiter',delimiter);
    lineData = lineData{1};                %# Remove cell encapsulation
    if strcmp(datagrid_string{iLine}(end),delimiter)   %# Account for when
the line
      lineData{end+1} = '';                         %#   ends with a delimiter
    end
    datagrid_string(iLine,1:numel(lineData)) = lineData;   %# Overwrite line
data
  end

% featgrid = str2double(datagrid_string);  % converts the data into numbers

%% Sort matrix by name
% strfind(datagrid_string(10,7),'B');
datagrid_string  =  sortrows(datagrid_string,3);  %  Important  step:  Sort
martix by name to compare right values further on

%% Convert mea std from string to double
sigma_mea  =  datagrid_string(:,length(datagrid_string(1,:))-2);  %  std  is
represented in the 115th column in datagrid_string
sigma_mea = str2double(sigma_mea);
```

```
%% Copy measuredata and not metadata, calculations etc
datagrid_mod = datagrid_string(:,6:end-12);

%% Remove empty columns
k=1;
while  k<length(datagrid_mod(1,:))  %  Step  through  the  matrix  column  by
column. Cannot use for since columns are sometimes removed and numbering is
changed.
    if isempty(datagrid_mod{1,k})==1 % If column is empty
        datagrid_mod(:,k)=[]; % Remove column
    else
        k=k+1;
    end
end

%% Transform from letters to + or -
datagrid_num = zeros(size(datagrid_mod,1),size(datagrid_mod,2));
for r=1:size(datagrid_mod,1)
    for c=1:size(datagrid_mod,2)
        if  datagrid_mod{r,c}(end)  ==  'H'  ||  datagrid_mod{r,c}(end)  ==  'O'
|| datagrid_mod{r,c}(end) == 'B'
            datagrid_num(r,c) = str2double(datagrid_mod{r,c}(1:4));
        elseif  datagrid_mod{r,c}(end)  ==  'F'  ||  datagrid_mod{r,c}(end)  ==
'I' || datagrid_mod{r,c}(end) == 'L'
            datagrid_num(r,c) = -1*str2double(datagrid_mod{r,c}(1:4));
        end
    end
end

%% Rearrange the data so s-chart can be plotted
numofcol = length(datagrid_num(1,:));
numofrow = length(datagrid_num(:,1));
for k=1:numofrow
    for i=1:numofcol-3
        cc_data(i,1,k) = datagrid_num(k,i); % Copy data into control chart
matrix. cc_data('measure occasion' , 'window step' , 'point').
        cc_data(i,2,k) = datagrid_num(k,i+1);
        cc_data(i,3,k) = datagrid_num(k,i+2);
        cc_data(i,4,k) = datagrid_num(k,i+3);
    end
end

%% Control charts to identify leaps
%controlchart(cc_data(:,:,1),'chart',{'xbar' 's'})
%controlchart(cc_data(:,:,2),'chart',{'xbar' 's'})
controlchart(cc_data(:,:,3),'chart',{'xbar' 's'})
%controlchart(cc_data(:,:,4),'chart',{'xbar' 's'})
%controlchart(cc_data(:,:,5),'chart',{'xbar' 's'})
%controlchart(cc_data(:,:,6),'chart',{'xbar' 's'})
%controlchart(cc_data(:,:,7),'chart',{'xbar' 's'})
%controlchart(cc_data(:,:,8),'chart',{'xbar' 's'})
%controlchart(cc_data(:,:,9),'chart',{'xbar' 's'})
%controlchart(cc_data(:,:,10),'chart',{'xbar' 's'})
%controlchart(cc_data(:,:,11),'chart',{'xbar' 's'})

%% Calculate the standard deviations
stdev = zeros(numofrow,numofcol-3); % Prepare the stdev matrix
for k=1:numofrow % Step row by row
    for i=1:numofcol-3 % Step column by column
        stdev(k,i)                                                          =
std([datagrid_num(k,i),datagrid_num(k,i+1),datagrid_num(k,i+2),datagrid_num
```

```
(k,i+3)]); % Calculate the std of the small window
    end
end
%% Calculate mean of stdev
for k=1:numofrow
    mean_stdev(k) = mean(stdev(k,:));
end
mean_stdev = mean_stdev'

%% Calculate CL
%c4_3 = 0.8862;
c4_4 = 0.9213;
for k=1:length(stdev(:,1))
    UCL(k) = mean_stdev(k)+3*mean_stdev(k)/c4_4*sqrt(1-c4_4^2);
end
for k=1:length(stdev(:,1))
    LCL(k) = mean_stdev(k)-3*mean_stdev(k)/c4_4*sqrt(1-c4_4^2);
end

%% Remove stdev values out of control
new_stdev = stdev;
for i=1:length(new_stdev(:,1))
    k=1;
    while  k<length(new_stdev(1,:))  %  Step  through  the  matrix  column  by
column. Cannot use for since columns are sometimes removed and numbering is
changed.
        if new_stdev(i,k) > UCL(i) || new_stdev(i,k) < LCL(i) % If stdev is
out of control
            new_stdev(:,k)=[]; % Remove column, i.e. stdev
        else
            k=k+1;
        end
    end
end

%% Calculate new mean of stdev, after outliers have been removed
for k=1:numofrow
    new_mean_stdev(k) = mean(new_stdev(k,:));
end
new_mean_stdev = new_mean_stdev'

% %% Iteration
% %% Calculate CL
% %c4_3 = 0.8862;
% c4_4 = 0.9213;
% for k=1:length(stdev(:,1))
%     UCL(k) = new_mean_stdev(k)+3*new_mean_stdev(k)/c4_4*sqrt(1-c4_4^2);
% end
% for k=1:length(stdev(:,1))
%     LCL(k) = new_mean_stdev(k)-3*new_mean_stdev(k)/c4_4*sqrt(1-c4_4^2);
% end
%
% %% Remove stdev values out of control
% new2_stdev = new_stdev;
% for i=1:length(new2_stdev(:,1))
%     k=1;
%      while k<length(new2_stdev(1,:)) % Step through the matrix column by
column. Cannot use for since columns are sometimes removed and numbering is
changed.
%            if  new2_stdev(i,k)  >  UCL(i)  ||  new2_stdev(i,k)  <  LCL(i)  %  If
stdev is out of control
%              new2_stdev(:,k)=[]; % Remove column, i.e. stdev
```

```
%           else
%               k=k+1;
%           end
%       end
% end
%
% %% Calculate new mean of stdev, after outliers have been removed
% for k=1:numofrow
%     new2_mean_stdev(k) = mean(new2_stdev(k,:));
% end
% new2_mean_stdev = new2_mean_stdev'

%%
sigma_mea_new = new_mean_stdev;



%% Compare measure data and simulated data

%% Import RDnt
sim_rdt=textread(filename_sim);
sim_rdt(:,length(sim_rdt(1,:))) = []; % Takes away the last column which
includes 0s.

for k=1:length(sim_rdt(1,:))          % Calculates sigma for simulated data
for each point
    sigma_rdt(k)=std(sim_rdt(:,k));
end
sigma_rdt=sigma_rdt';

%% Plot comparison
figure(2)
plot(6*sigma_rdt,'b')
hold on
plot(6*sigma_mea_new,'r')
legend('6\sigma simulated','6\sigma measured')
title(a,'fontweight','bold','fontsize',12)
set(legend,'FontSize',11);
xlim([0 lineIndex])
ylim([0 3])
set(gca, 'XTick',[5 10 15 20 25 30 35 40])
set(gca,'FontSize',11)
xlabel('Measure point')
ylabel('mm')


sigma_dif = sigma_mea_new - sigma_rdt;

figure(3)
plot(6*sigma_dif)

%%
% If you get the following message you have to fix the datagrid so it does
not contain empty cells.
% This is done in CM4D
%
% Subscript indices must either be real positive integers or logicals.
% % Error in Combined_Transform_ws4_and_Plot (line 67)
%           if datagrid_mod{r,c}(end) == 'H' || datagrid_mod{r,c}(end) == 'O'
|| datagrid_mod{r,c}(end) == 'B'
```

Code for plotting measured data with simulated data

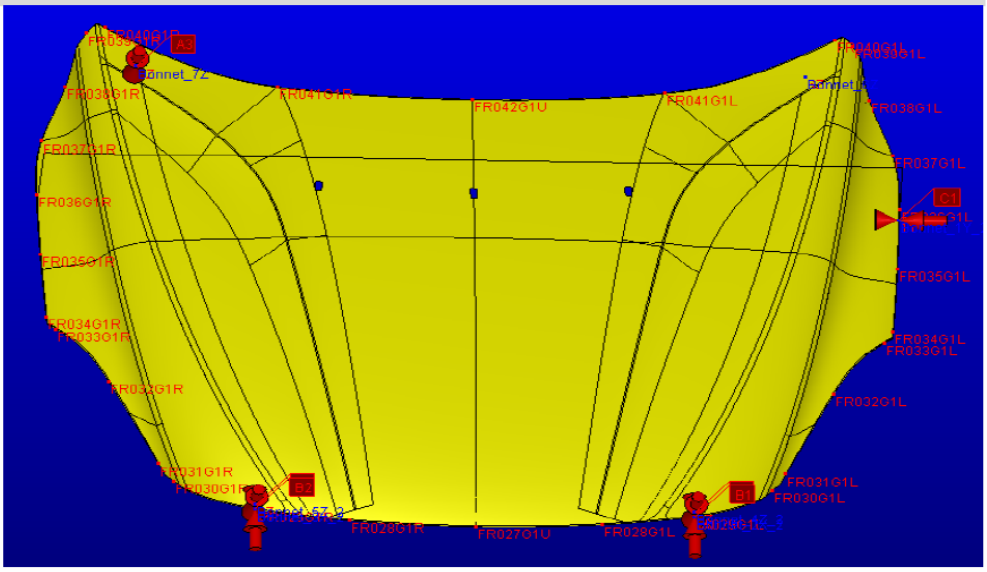
```
clear all
close all
clc
%% Open the datagrid file and convert to a matrix
delimiter=char(','); % Where to create a new cell
fid = fopen('DataGrid21Flush.csv','r');    %# Open the file

  datagrid_string = cell(10000,1);      %# Preallocate memory
  lineIndex = 1;                   %# Index of cell to place the next line in
  nextLine = fgetl(fid);            %# Read the first line from the file, fgetl
reads the next line in the file
  nextLine = fgetl(fid);           %# Read the second line from the file
  nextLine = fgetl(fid);

  while ~isequal(nextLine,-1)           %# Loop while not at the end of the
file, which -1 indicates
    datagrid_string{lineIndex} = nextLine;   %# Add the line to the cell
array
    lineIndex = lineIndex+1;           %# Increment the line index, to go to
the next line in the matrix 'featgrid'
    nextLine = fgetl(fid);             %# Read the next line from the file
  end

  fclose(fid);                     %# Close the file
  datagrid_string = datagrid_string(1:lineIndex-1);  %# Remove empty cells,
if needed

  % Now it is time to sort the data into columns

  for iLine = 1:lineIndex-1                %# Loop over lines
    lineData = textscan(datagrid_string{iLine},'%s',...  %# Read strings
                        'Delimiter',delimiter);
    lineData = lineData{1};                %# Remove cell encapsulation
    if strcmp(datagrid_string{iLine}(end),delimiter)   %# Account for when
the line
      lineData{end+1} = '';                     %#   ends with a delimiter
    end
    datagrid_string(iLine,1:numel(lineData)) = lineData;  %# Overwrite line
data
  end

% featgrid = str2double(datagrid_string);  % converts the data into numbers

% strfind(datagrid_string(10,7),'B');
datagrid_string  =  sortrows(datagrid_string,3);  %  Important  step:  Sort
martix by name to compare right values further on

%% Convert mea std from string to double
sigma_mea  =  datagrid_string(:,length(datagrid_string(1,:))-2);  %  std  is
represented in the 115th column in datagrid_string
sigma_mea = str2double(sigma_mea);

%% Import RDnt
sim_rdt=textread('V40Flush.txt');
sim_rdt(:,length(sim_rdt(1,:))) = []; % Takes away the last column which
includes 0s.

for k=1:length(sim_rdt(1,:))          % Calculates sigma for simulated data
for each point
```

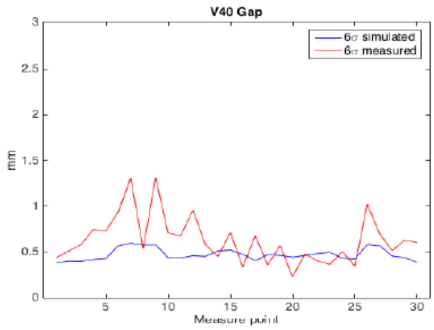
```
    sigma_rdt(k)=std(sim_rdt(:,k));
end
sigma_rdt=sigma_rdt';

%% Plot comparison
plot(6*sigma_rdt,'b')
hold on
plot(6*sigma_mea,'r')
legend('std simulated','std measured')
xlim([0 lineIndex])
ylim([0 3])
set(gca, 'XTick', [1 2 3 4 5 6 7 8 9 10 11])

sigma_dif = sigma_mea - sigma_rdt;

figure(2)
plot(6*sigma_dif)
```

Appendix 4: Translation tables

V40 Bonnet - Gap

Number	Name
1	FR027G1U
2	FR028G1L
3	FR028G1R
4	FR029G1L
5	FR029G1R
6	FR030G1L
7	FR030G1R
8	FR031G1L
9	FR031G1R
10	FR032G1L
11	FR032G1R
12	FR033G1L
13	FR033G1R
14	FR034G1L
15	FR034G1R
16	FR035G1L
17	FR035G1R
18	FR036G1L
19	FR036G1R
20	FR037G1L
21	FR037G1R
22	FR038G1L
23	FR038G1R
24	FR039G1L
25	FR039G1R
26	FR040G1L
27	FR040G1R
28	FR041G1L
29	FR041G1R
30	FR042G1U





V40 Bonnet - Flush

Number	Name
1	FR027F1U
2	FR028F1L
3	FR028F1R
4	FR029F1L
5	FR029F1R
6	FR030F1L
7	FR030F1R
8	FR031F1L
9	FR031F1R
10	FR032F1L
11	FR032F1R
12	FR033F1L
13	FR033F1R
14	FR034F1L
15	FR034F1R
16	FR035F1L
17	FR035F1R
18	FR036F1L
19	FR036F1R
20	FR037F1L
21	FR037F1R
22	FR038F1L
23	FR038F1R
24	FR039F1L
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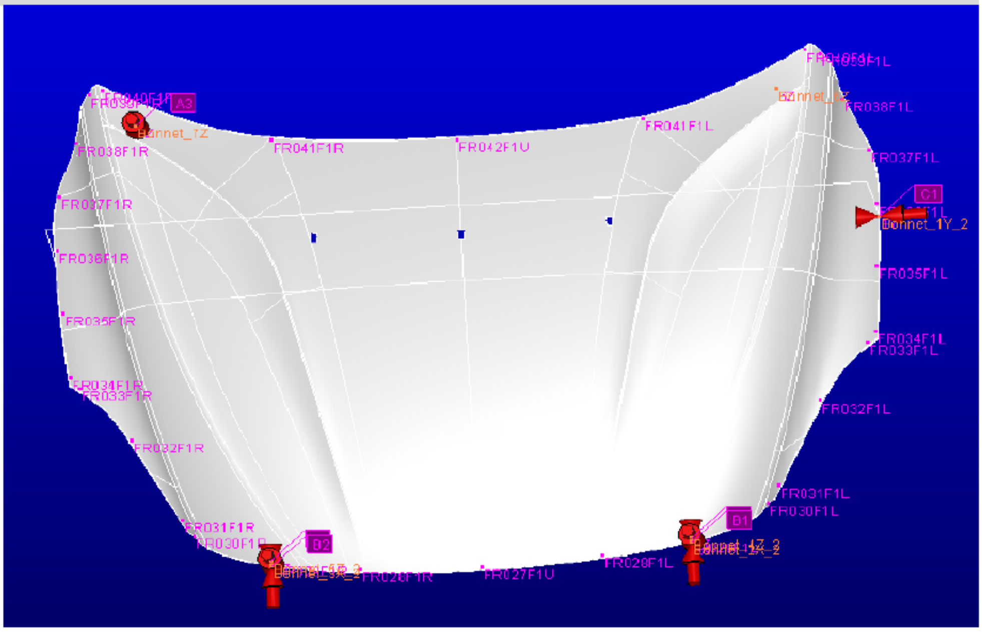
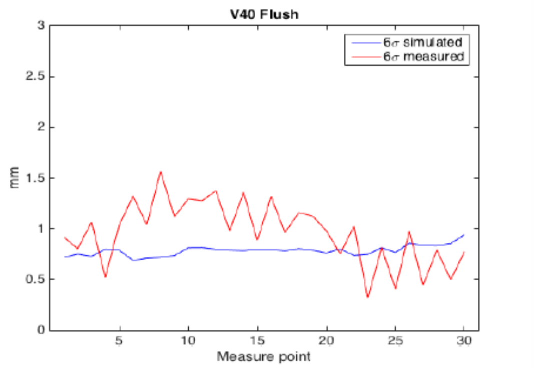
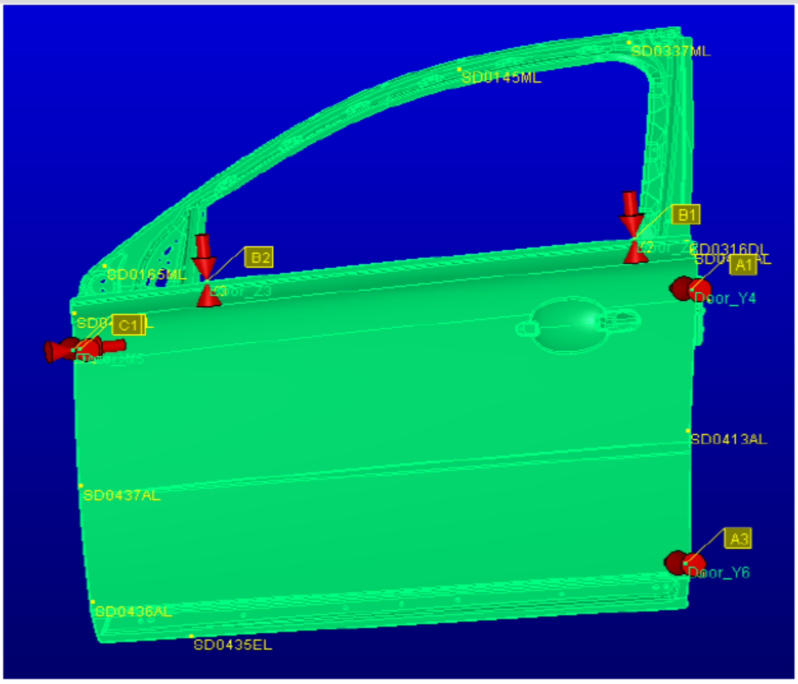
26	FR040F1L
27	FR040F1R
28	FR041F1L
29	FR041F1R
30	FR042F1U

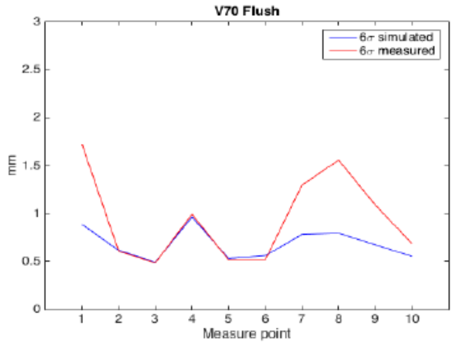




V70 Front Door - Flush

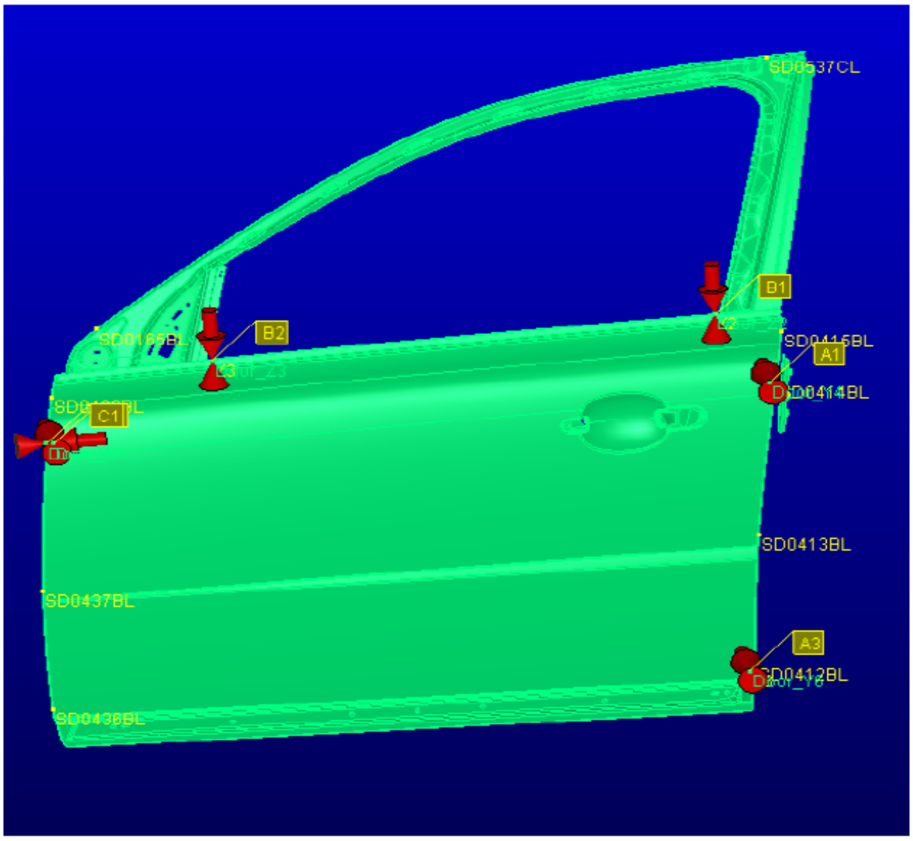
Number	Name
1	SD0145ML
2	SD0165ML
3	SD0316DL
4	SD0337ML
5	SD0413AL
6	SD0415AL
7	SD0435EL
8	SD0436AL
9	SD0437AL
10	SD0439AL

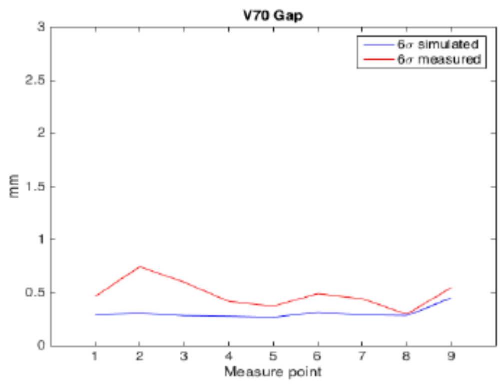




V70 Front Door - Gap

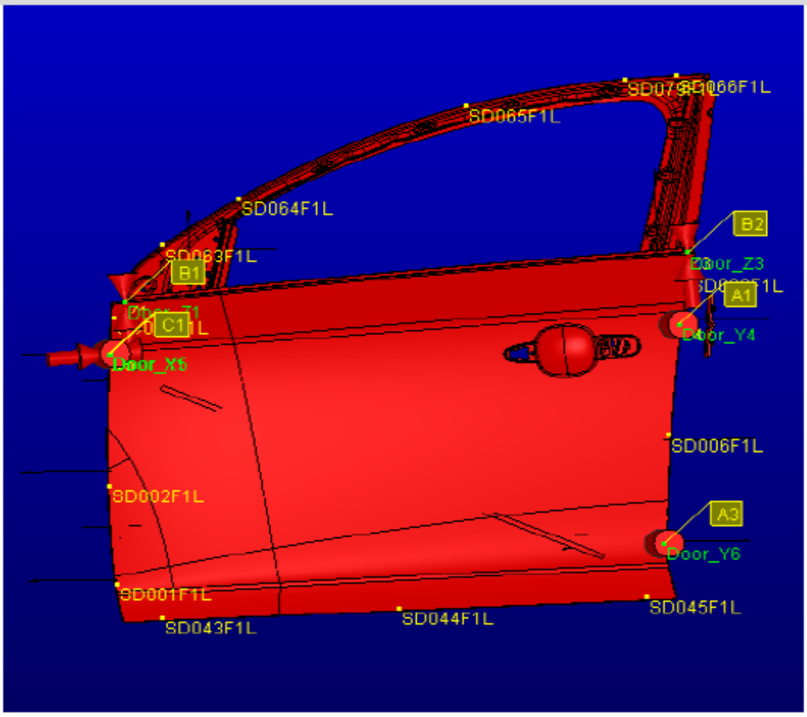
Number	Name
1	SD0165BL
2	SD0412BL
3	SD0413BL
4	SD0414BL
5	SD0415BL
6	SD0436BL
7	SD0437BL
8	SD0439BL
9	SD0537CL

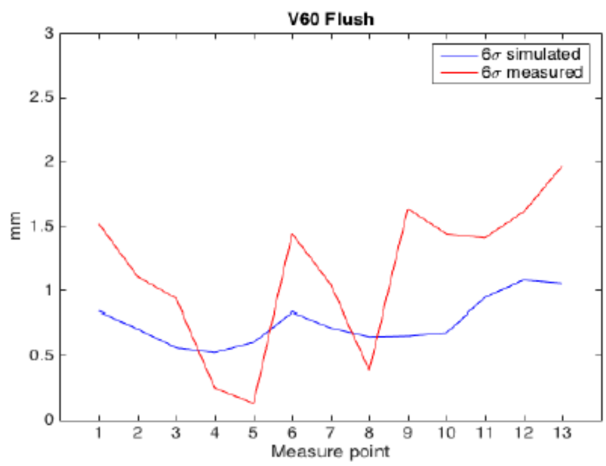




V60 Front Door - Flush

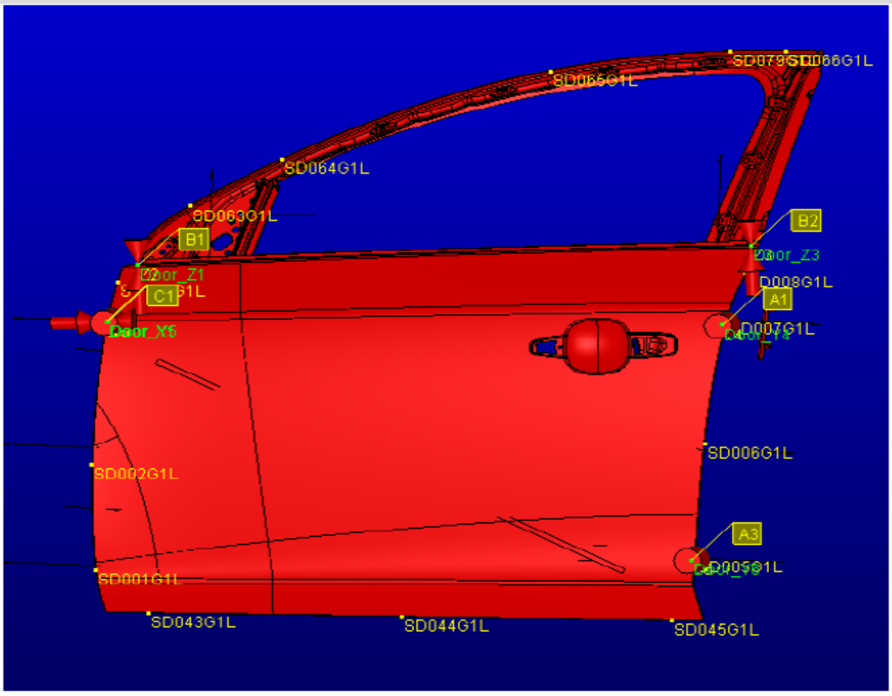
Number	Name
1	SD001F1L
2	SD002F1L
3	SD004F1L
4	SD006F1L
5	SD008F1L
6	SD043F1L
7	SD044F1L
8	SD045F1L
9	SD063F1L
10	SD064F1L
11	SD065F1L
12	SD066F1L
13	SD079F1L

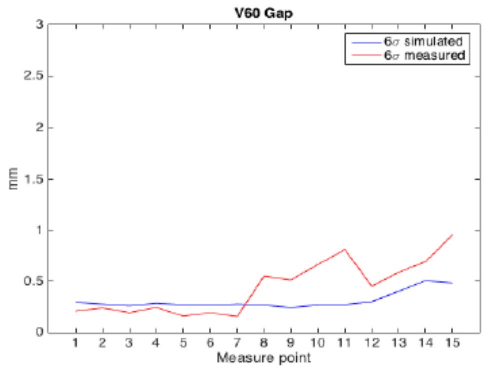




V60 Front Door - Gap

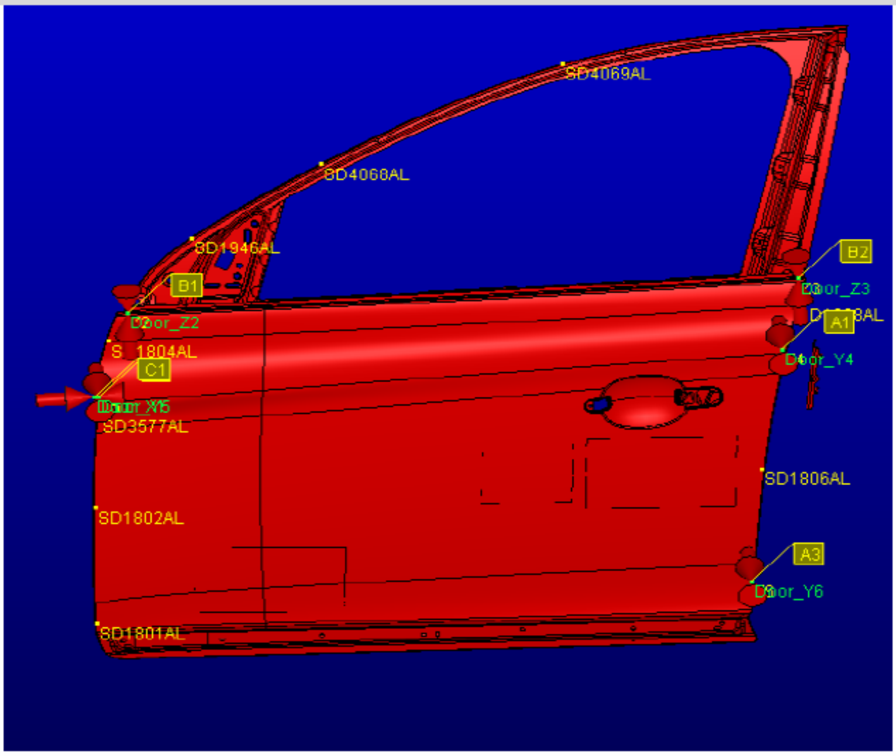
Number	Name
1	SD001G1L
2	SD002G1L
3	SD004G1L
4	SD005G1L
5	SD006G1L
6	SD007G1L
7	SD008G1L
8	SD043G1L
9	SD044G1L
10	SD045G1L
11	SD063G1L
12	SD064G1L
13	SD065G1L
14	SD066G1L
15	SD079G1L

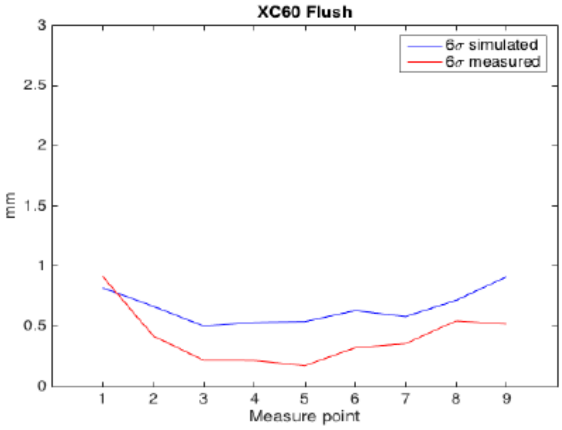




XC60 Front Door - Flush

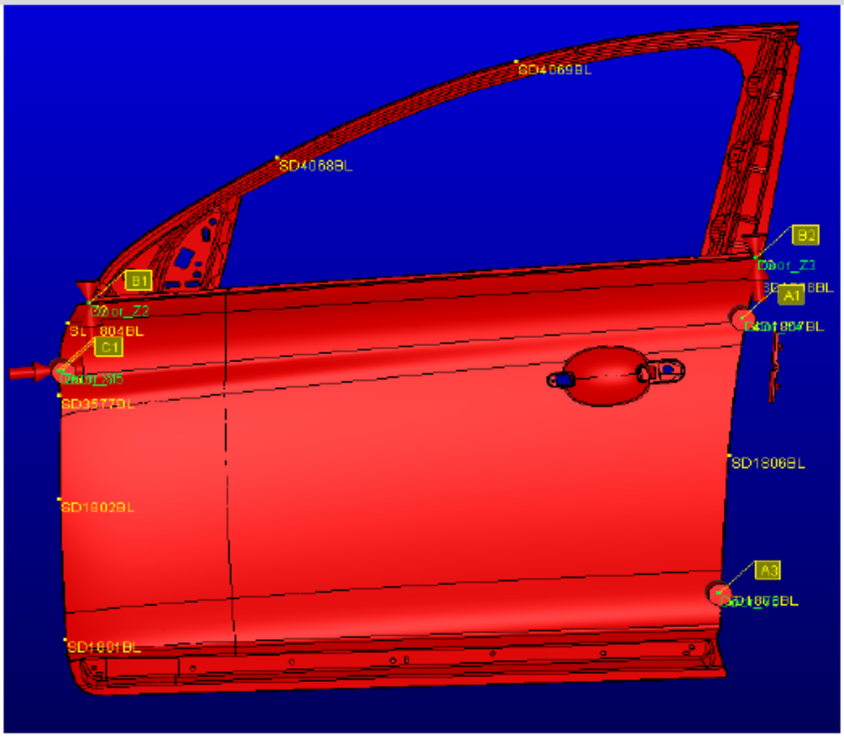
Number	Name
1	SD1801AL
2	SD1802AL
3	SD1804AL
4	SD1806AL
5	SD1808AL
6	SD1946AL
7	SD3577AL
8	SD4068AL
9	SD4069AL

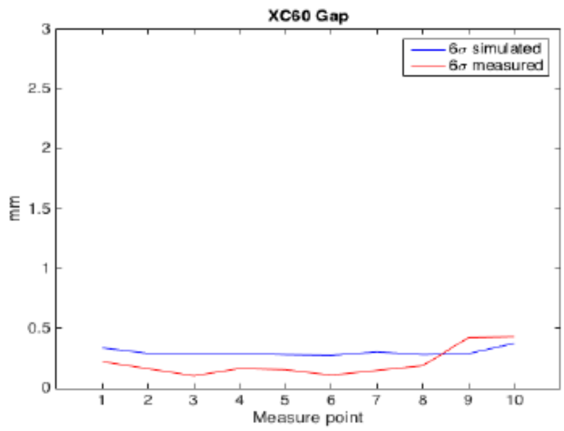




XC60 Front Door - Gap

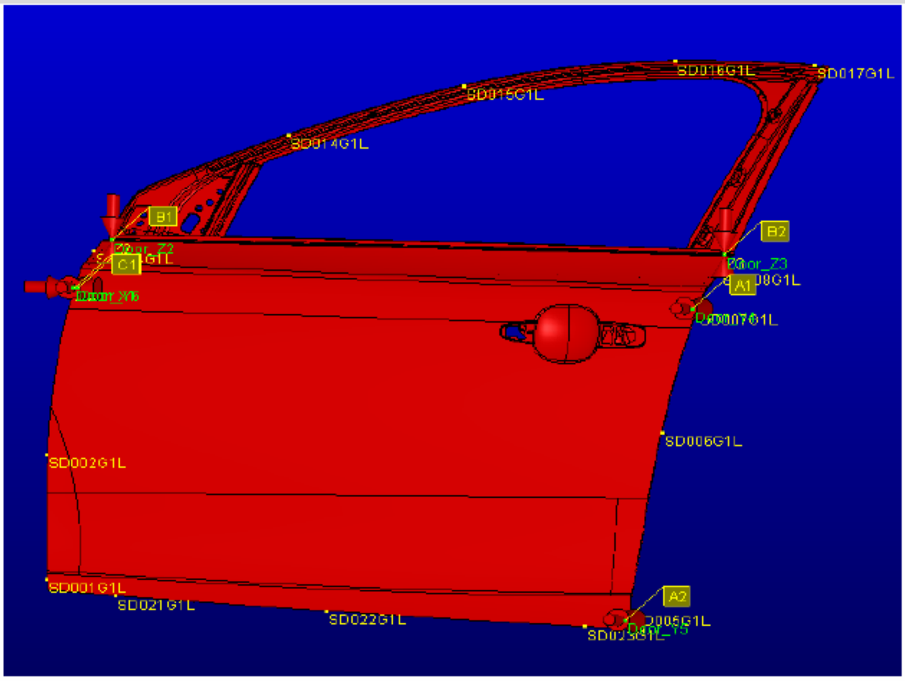
Number	Name
1	SD1801BL
2	SD1802BL
3	SD1804BL
4	SD1805BL
5	SD1806BL
6	SD1807BL
7	SD1808BL
8	SD3577BL
9	SD4068BL
10	SD4069BL

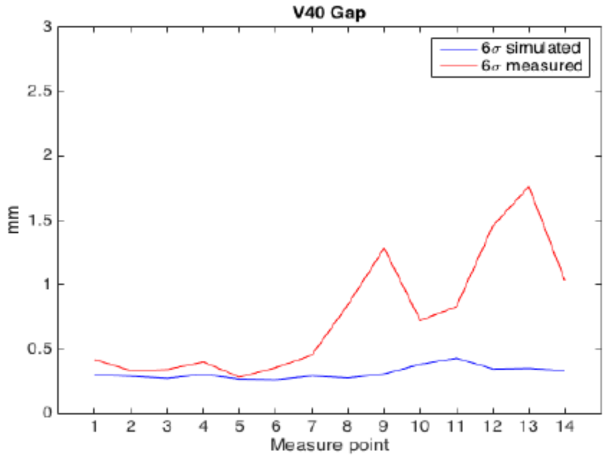




V40 Front Door - Gap

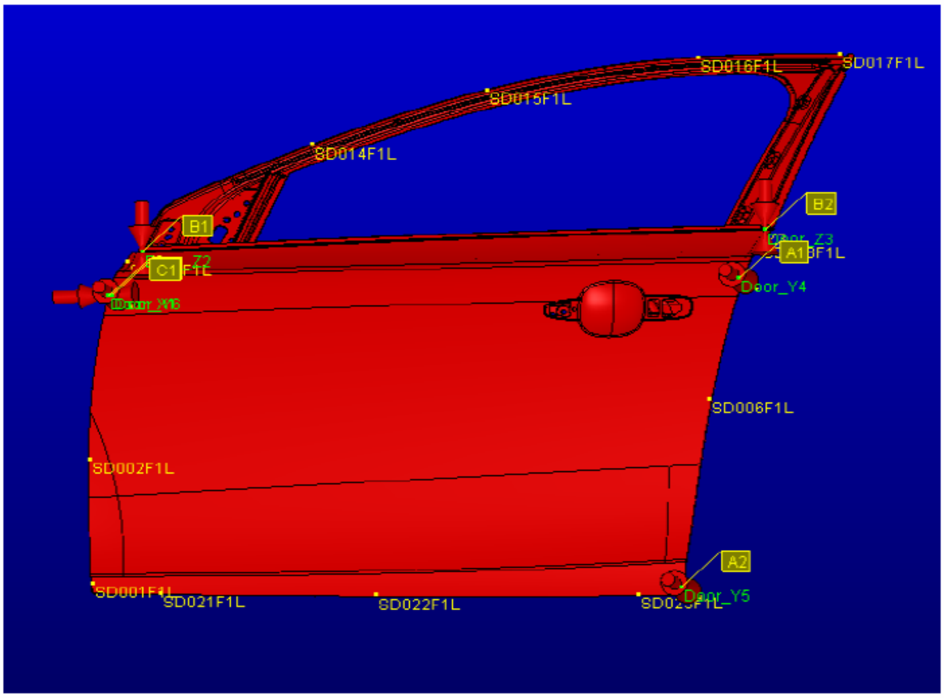
Number	Name
1	SD1801BL
2	SD1802BL
3	SD1804BL
4	SD1805BL
5	SD1806BL
6	SD1807BL
7	SD1808BL
8	SD3577BL
9	SD4068BL
10	SD4069BL

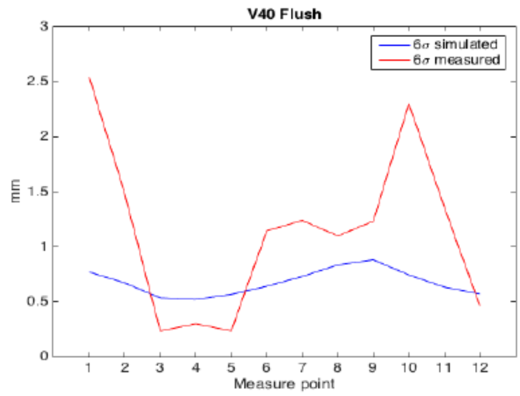




V40 Front Door - Flush

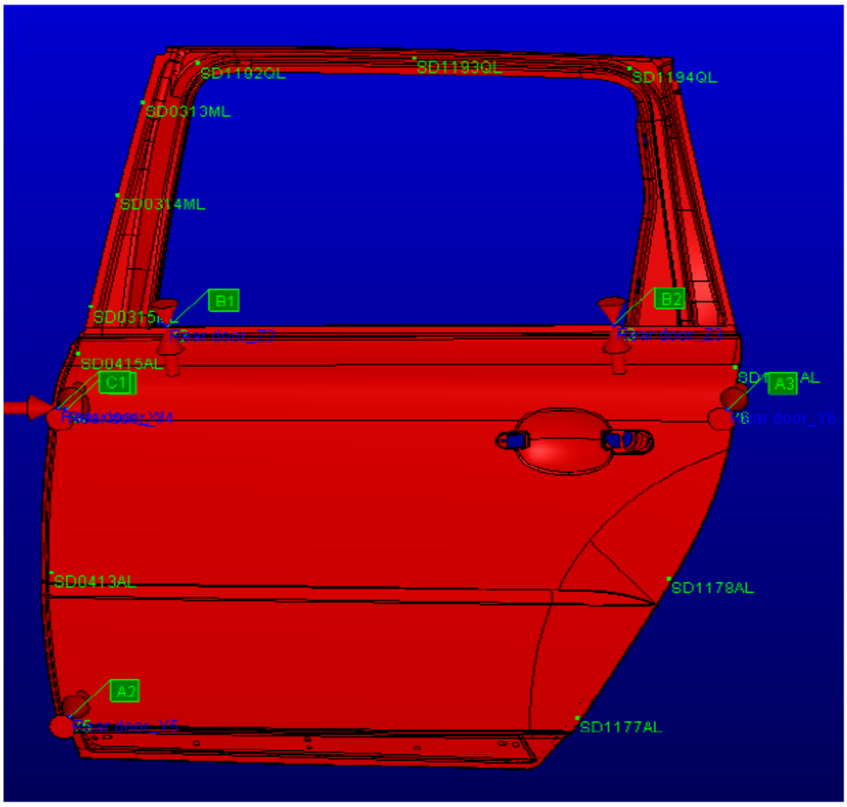
Number	Name
1	SD001G1L
2	SD002G1L
3	SD004G1L
4	SD005G1L
5	SD006G1L
6	SD007G1L
7	SD008G1L
8	SD014G1L
9	SD015G1L
10	SD016G1L
11	SD017G1L
12	SD021G1L
13	SD022G1L
14	SD023G1L

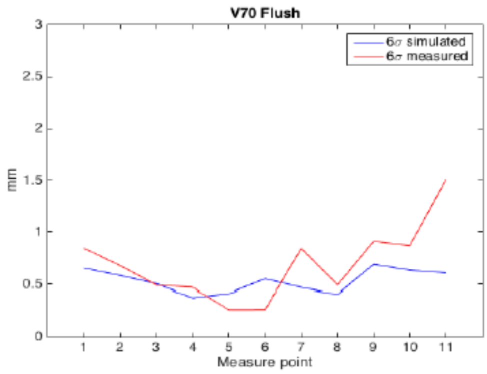




V70 Rear Door - Flush

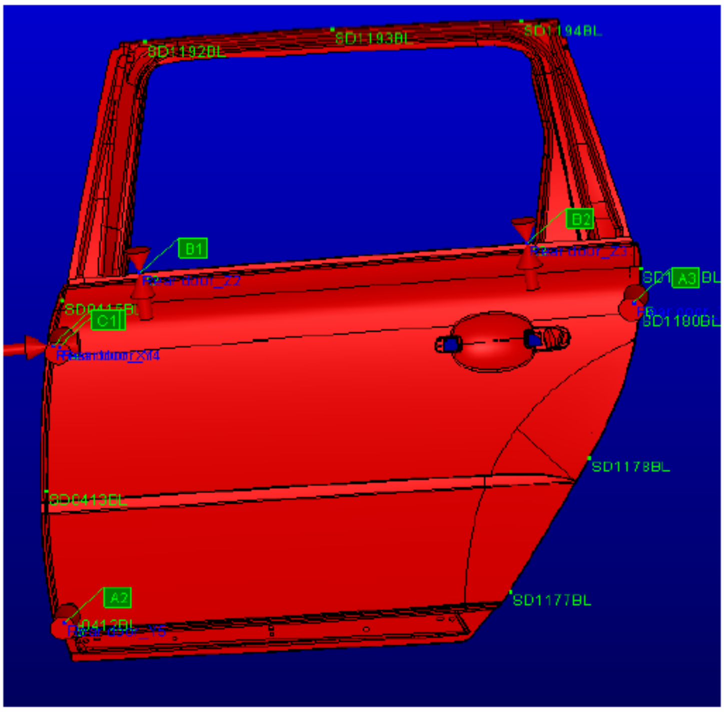
Number	Name
1	SD0313ML
2	SD0314ML
3	SD0315ML
4	SD0413AL
5	SD0415AL
6	SD1177AL
7	SD1178AL
8	SD1181AL
9	SD1192QL
10	SD1193QL
11	SD1194QL

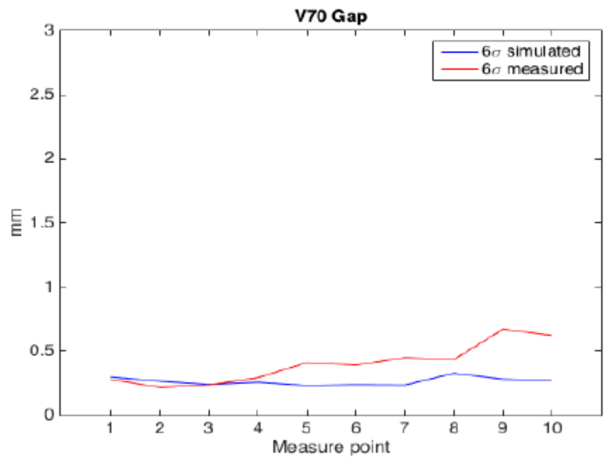




V70 Rear Door - Gap

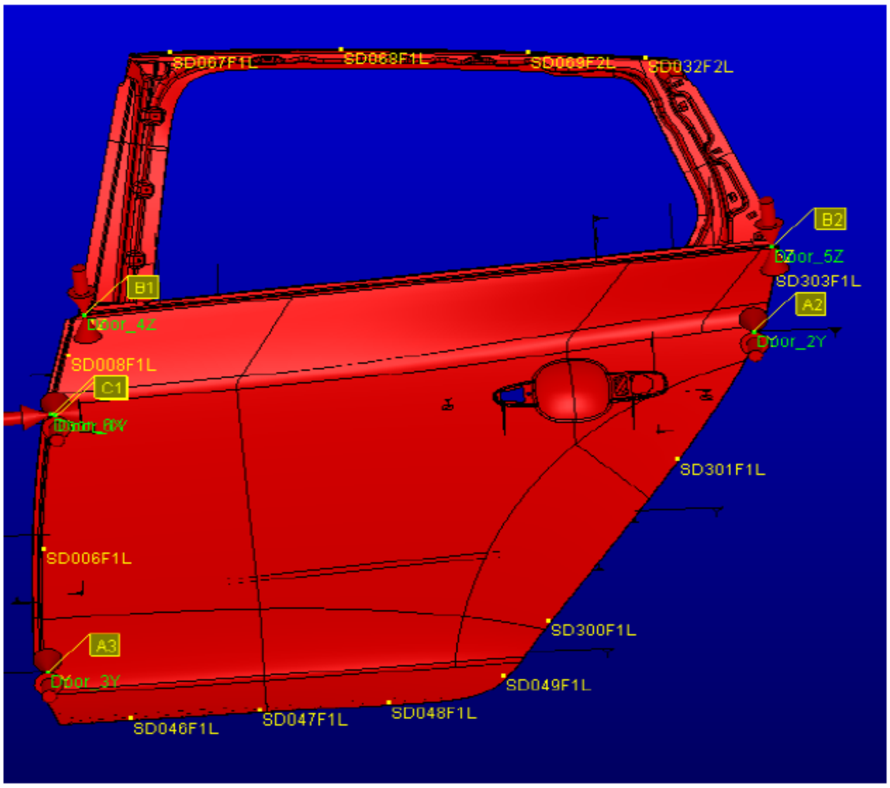
Number	Name
1	SD0412BL
2	SD0413BL
3	SD0415BL
4	SD1177BL
5	SD1178BL
6	SD1180BL
7	SD1181BL
8	SD1192BL
9	SD1193BL
10	SD1194BL

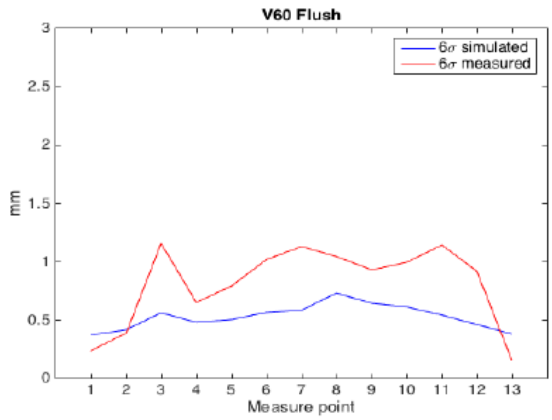




V60 Rear Door - Flush

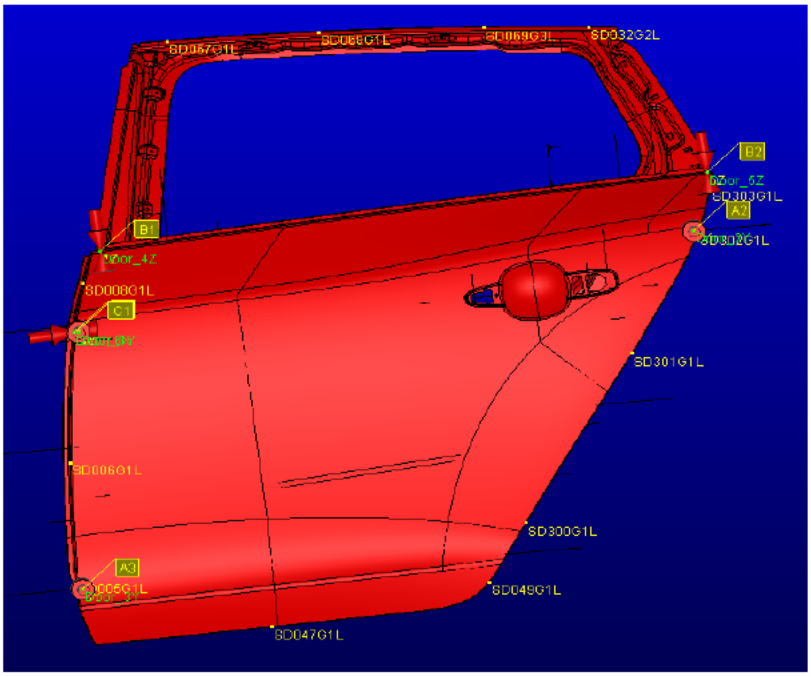
Number	Name
1	SD006F1L
2	SD008F1L
3	SD032F2L
4	SD046F1L
5	SD047F1L
6	SD048F1L
7	SD049F1L
8	SD067F1L
9	SD068F1L
10	SD069F2L
11	SD300F1L
12	SD301F1L
13	SD303F1L

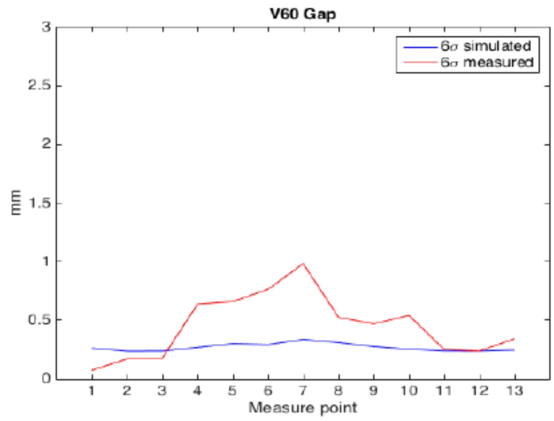




V60 Rear Door - Gap

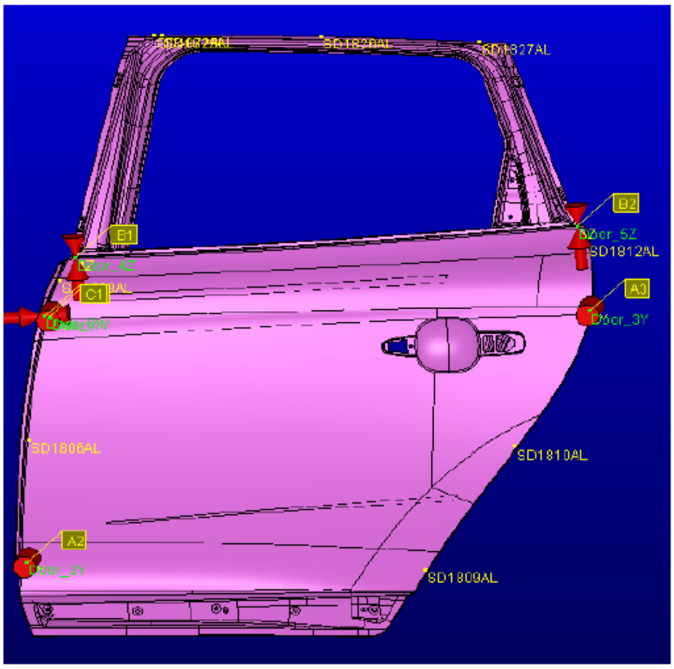
Number	Name
1	SD005G1L
2	SD006G1L
3	SD008G1L
4	SD032G2L
5	SD047G1L
6	SD049G1L
7	SD067G1L
8	SD068G1L
9	SD069G3L
10	SD300G1L
11	SD301G1L
12	SD302G1L
13	SD303G1L

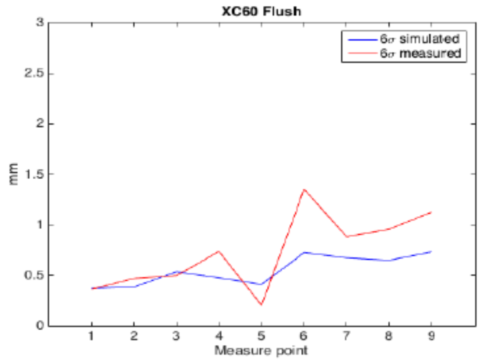




XC60 Rear Door - Flush

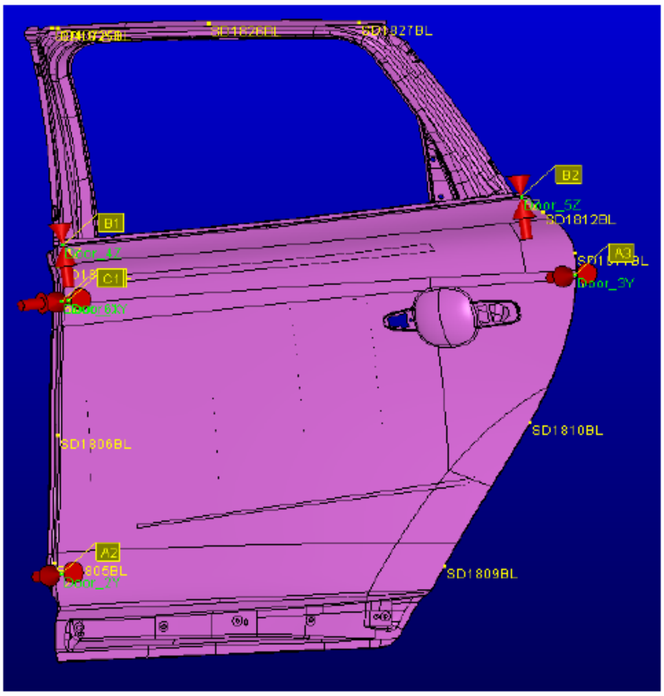
Number	Name
1	SD1806AL
2	SD1808AL
3	SD1809AL
4	SD1810AL
5	SD1812AL
6	SD1825AL
7	SD1826AL
8	SD1827AL
9	SD4072AL

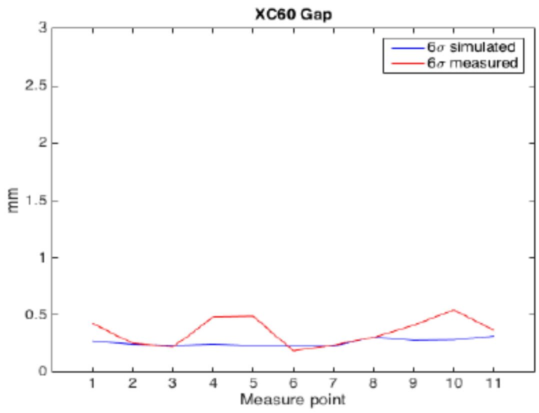




XC60 Rear Door - Gap

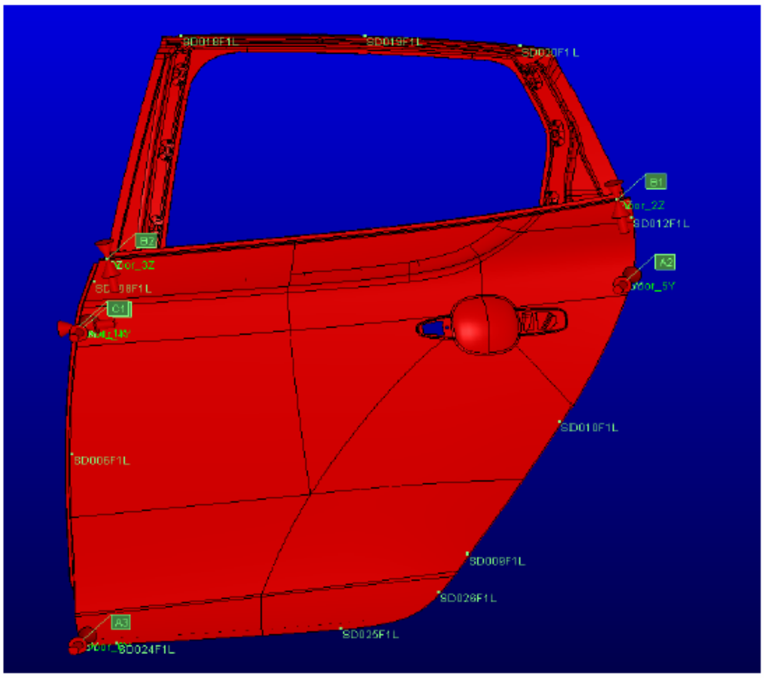
Number	Name
1	SD1805BL
2	SD1806BL
3	SD1808BL
4	SD1809BL
5	SD1810BL
6	SD1811BL
7	SD1812BL
8	SD1825BL
9	SD1826BL
10	SD1827BL
11	SD4072BL

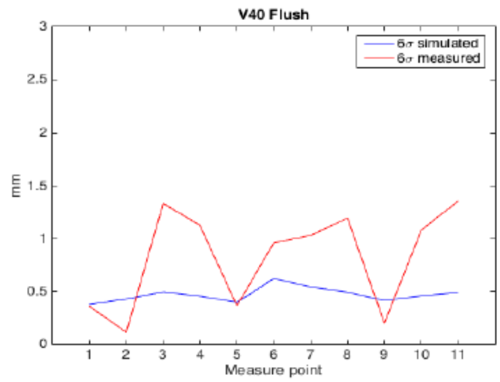




V40 Rear Door - Flush

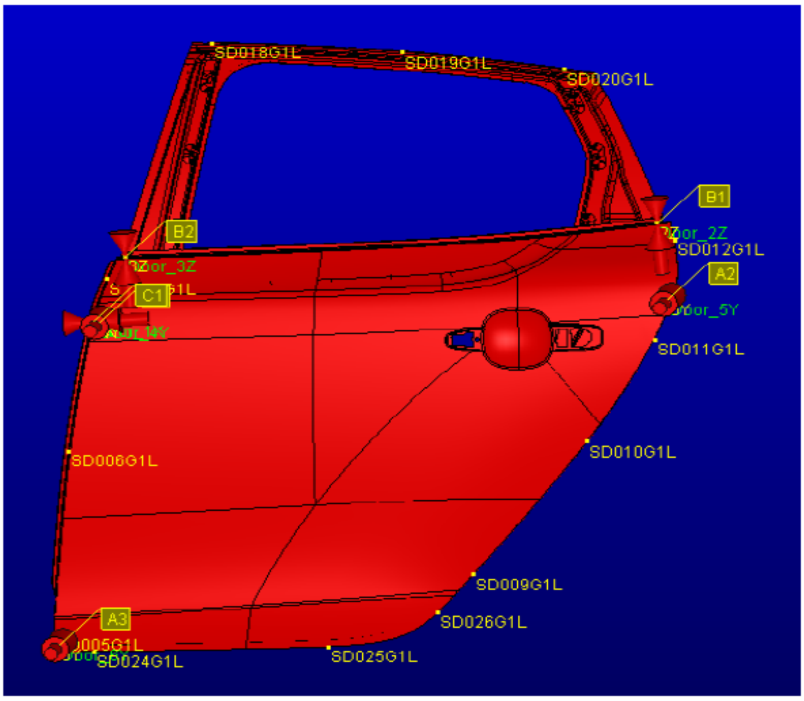
Number	Name
1	SD006F1L
2	SD008F1L
3	SD009F1L
4	SD010F1L
5	SD012F1L
6	SD018F1L
7	SD019F1L
8	SD020F1L
9	SD024F1L
10	SD025F1L
11	SD026F1L

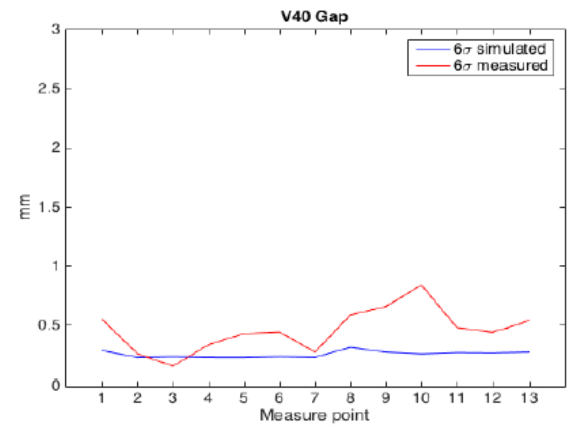




V40 Rear Door - Gap

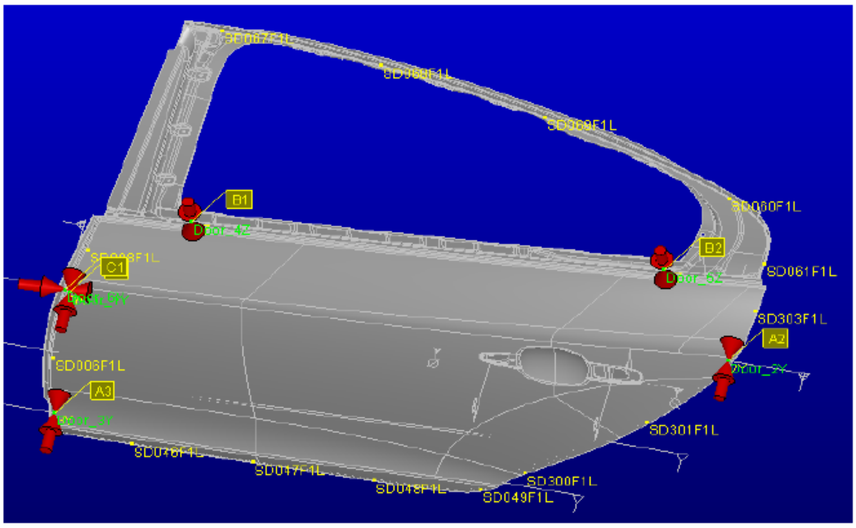
Number	Name
1	SD006F1L
2	SD008F1L
3	SD009F1L
4	SD010F1L
5	SD012F1L
6	SD018F1L
7	SD019F1L
8	SD020F1L
9	SD024F1L
10	SD025F1L
11	SD026F1L

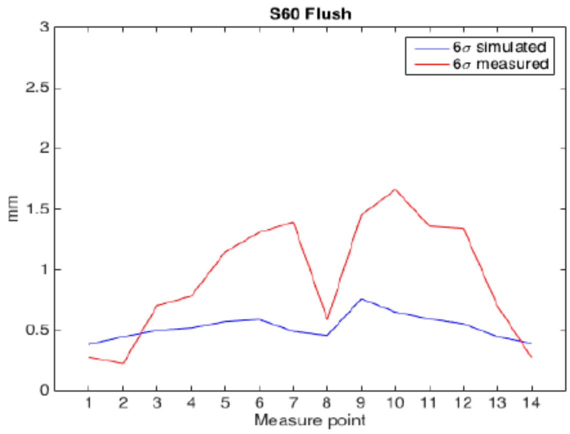




S60 Rear Door - Flush

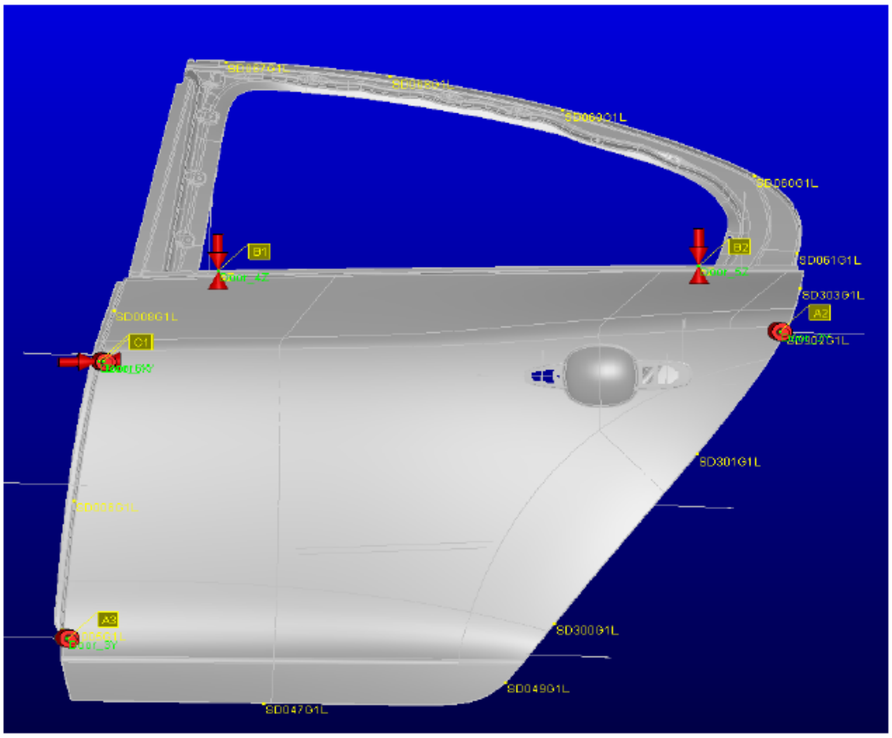
Number	Name
1	SD006F1L
2	SD008F1L
3	SD046F1L
4	SD047F1L
5	SD048F1L
6	SD049F1L
7	SD060F1L
8	SD061F1L
9	SD067F1L
10	SD068F1L
11	SD069F1L
12	SD300F1L
13	SD301F1L
14	SD303F1L

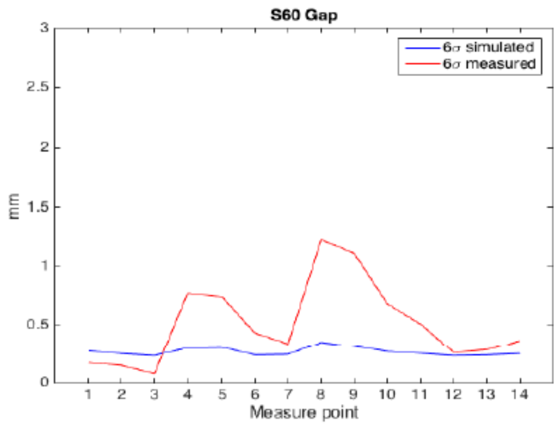




S60 Rear Door - Gap

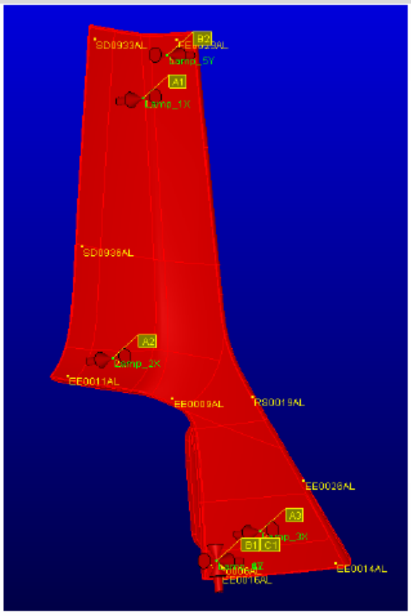
Number	Name
1	SD005G1L
2	SD006G1L
3	SD008G1L
4	SD047G1L
5	SD049G1L
6	SD060G1L
7	SD061G1L
8	SD067G1L
9	SD068G1L
10	SD069G1L
11	SD300G1L
12	SD301G1L
13	SD302G1L
14	SD303G1L

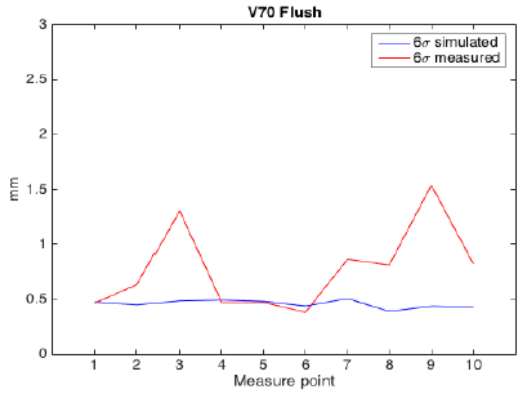




V70 Rear Lamp - Flush

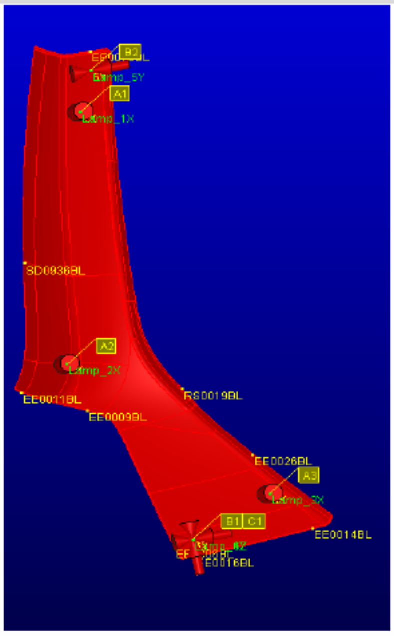
Number	Name
1	EE0006AL
2	EE0009AL
3	EE0011AL
4	EE0014AL
5	EE0016AL
6	EE0026AL
7	EE0029AL
8	RS0019AL
9	SD0933AL
10	SD0936AL

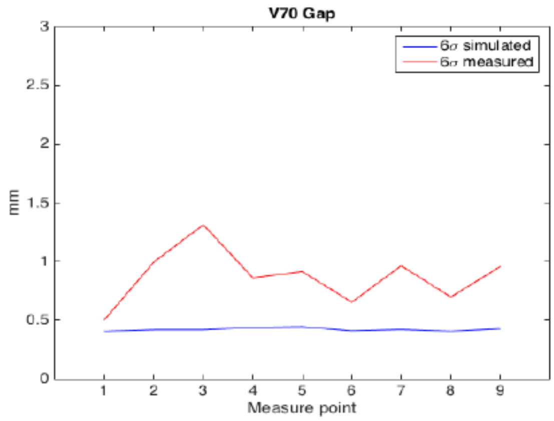




V70 Lamp Door - Gap

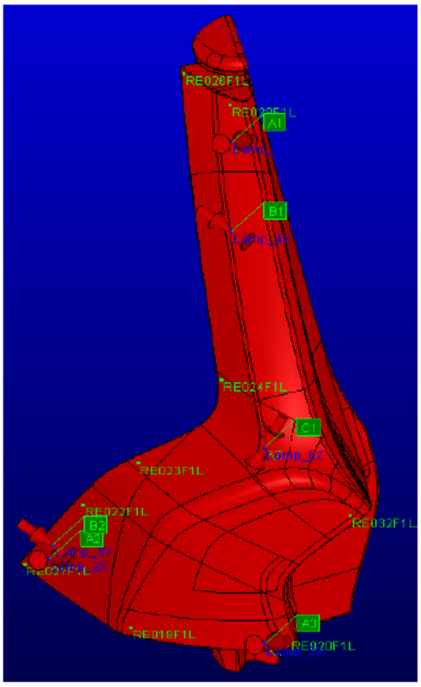
Number	Name
1	EE0006BL
2	EE0009BL
3	EE0011BL
4	EE0014BL
5	EE0016BL
6	EE0026BL
7	EE0029BL
8	RS0019BL
9	SD0936BL

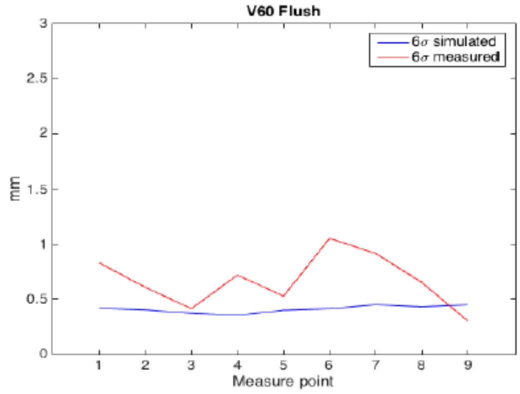




V60 Rear Lamp - Flush

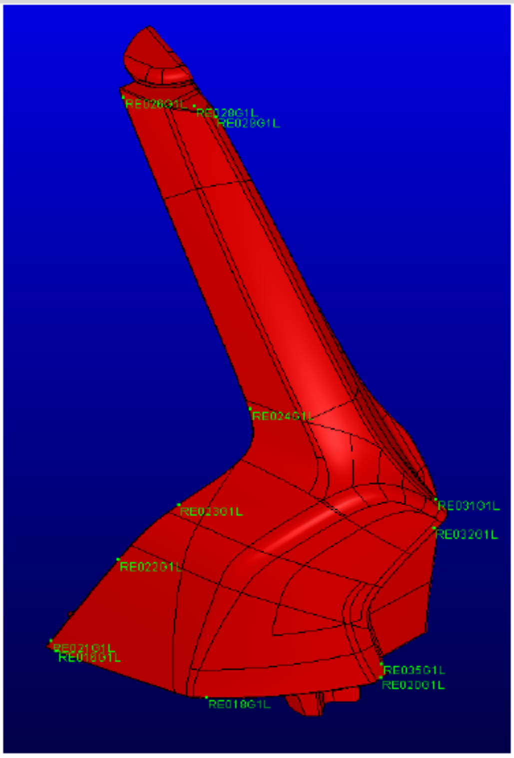
Number	Name
1	RE018F1L
2	RE020F1L
3	RE021F1L
4	RE022F1L
5	RE023F1L
6	RE024F1L
7	RE026F1L
8	RE028F1L
9	RE032F1L

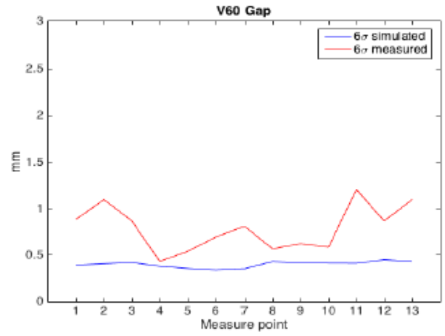




V60 Lamp Door - Gap

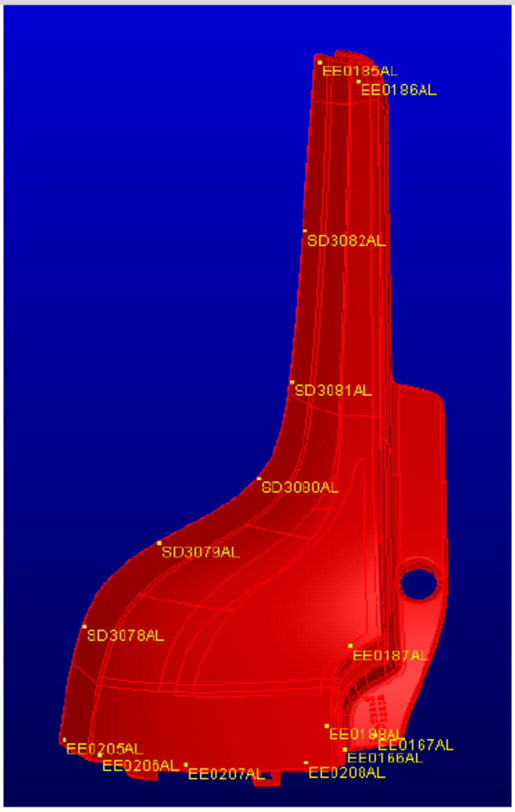
Number	Name
1	RE016G1L
2	RE018G1L
3	RE020G1L
4	RE021G1L
5	RE022G1L
6	RE023G1L
7	RE024G1L
8	RE026G1L
9	RE028G1L
10	RE029G1L
11	RE031G1L
12	RE032G1L
13	RE035G1L

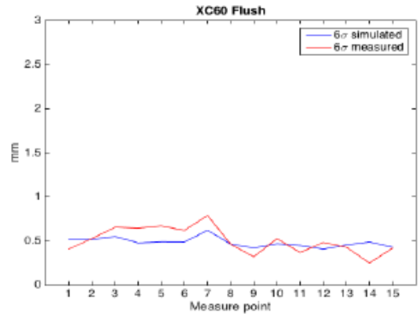




XC60 Rear Lamp - Flush

Number	Name
1	EE0166AL
2	EE0167AL
3	EE0185AL
4	EE0186AL
5	EE0187AL
6	EE0188AL
7	EE0205AL
8	EE0206AL
9	EE0207AL
10	EE0208AL
11	SD3078AL
12	SD3079AL
13	SD3080AL
14	SD3081AL
15	SD3082AL





XC60 Rear Lamp - Gap

Number	Name
1	EE0166BL
2	EE0167BL
3	EE0185BL
4	EE0186BL
5	EE0187BL
6	EE0188BL
7	EE0205BL
8	EE0206BL
9	EE0207BL
10	EE0208BL
11	RS0040BL
12	RS0041BL
13	RS0042BL
14	SD3077BL
15	SD3078BL
16	SD3079BL
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18	SD3081BL
19	SD3082BL
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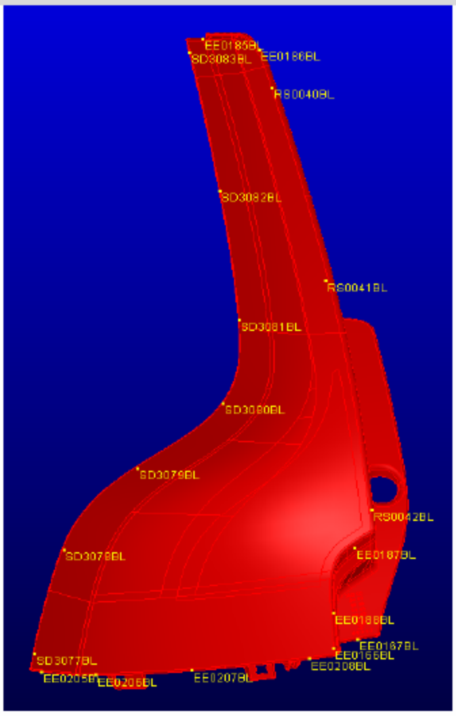
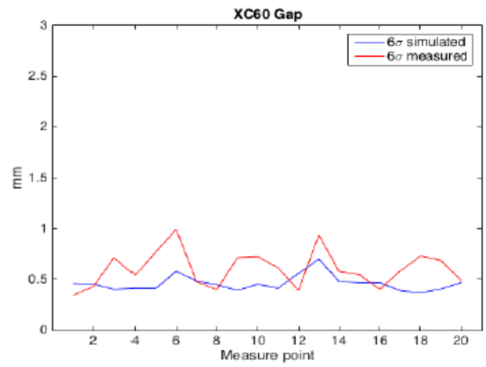
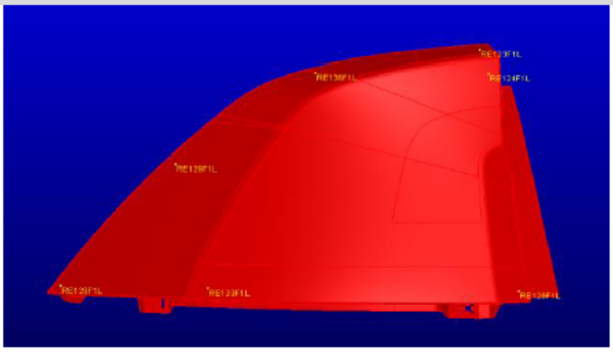
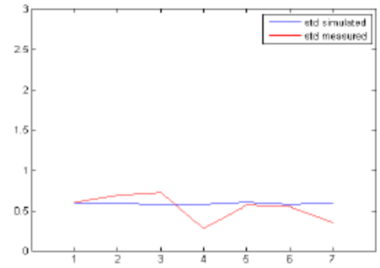




S60 Rear Lamp - Flush

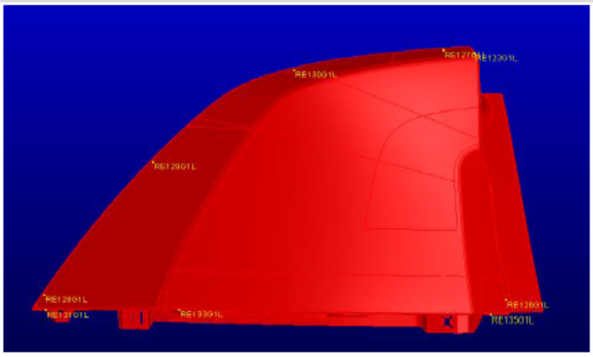
Number	Name
1	RE123F1L
2	RE124F1L
3	RE126F1L
4	RE128F1L
5	RE129F1L
6	RE130F1L
7	RE133F1L

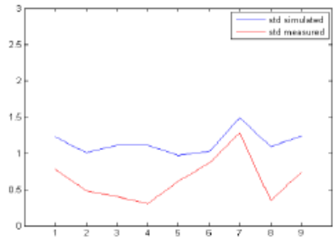




S60 Rear Lamp - Gap

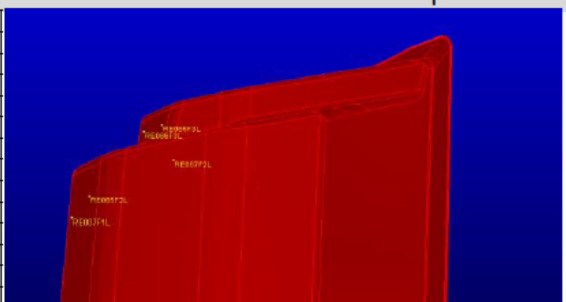
Number	Name
1	RE123G1L
2	RE126G1L
3	RE127G1L
4	RE128G1L
5	RE129G1L
6	RE130G1L
7	RE131G1L
8	RE133G1L
9	RE135G1L

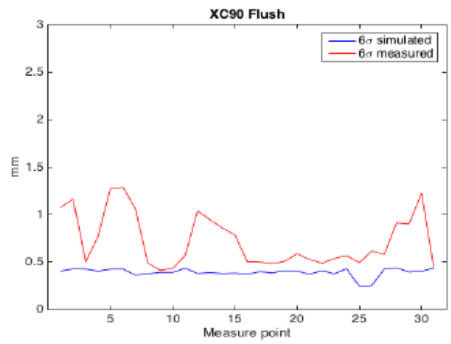


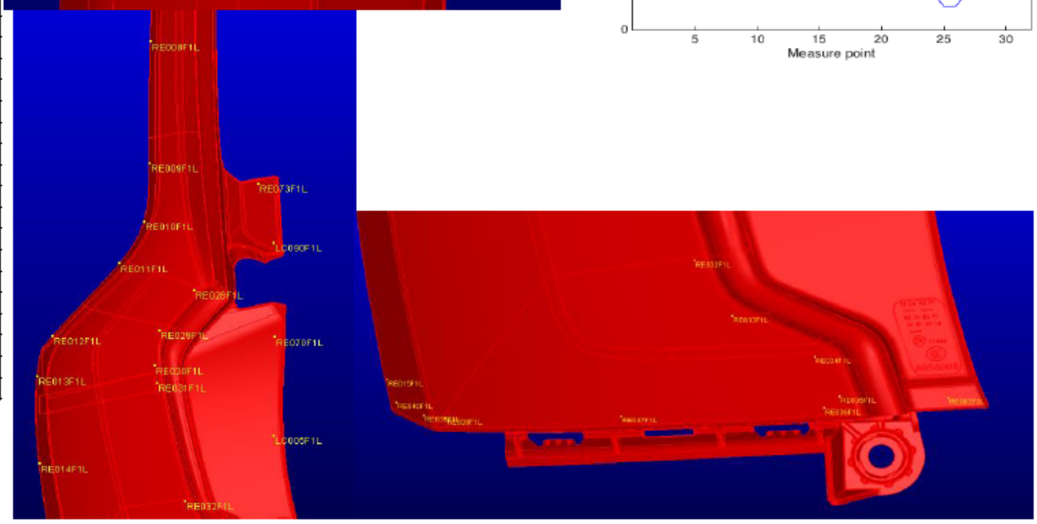


XC90 Rear Lamp - Flush

Number	Name
1	LC005F1L
2	LC090F1L
3	RE007F1L
4	RE008F1L
5	RE009F1L
6	RE010F1L
7	RE011F1L
8	RE012F1L
9	RE013F1L
10	RE014F1L
11	RE015F1L
12	RE028F1L
13	RE029F1L
14	RE030F1L
15	RE031F1L
16	RE032F1L
17	RE033F1L
18	RE034F1L
19	RE035F1L
20	RE036F1L
21	RE037F1L
22	RE038F1L
23	RE039F1L
24	RE040F1L
25	RE065F2L
26	RE065F3L
27	RE066F3L
28	RE067F2L
29	RE070F1L
30	RE073F1L
31	RE082F2L

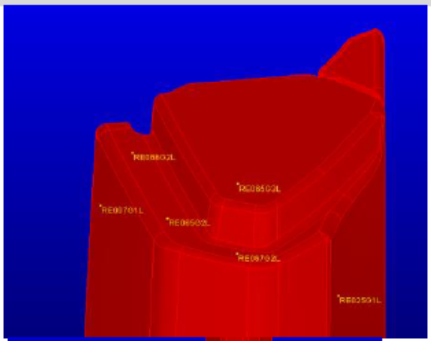


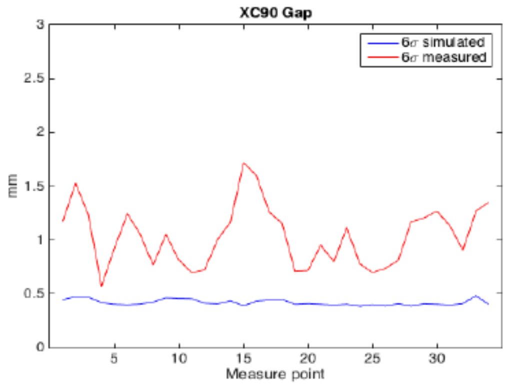


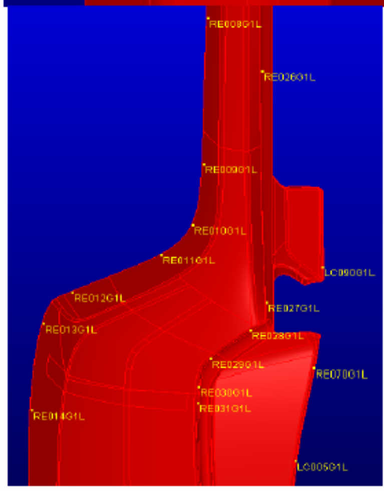


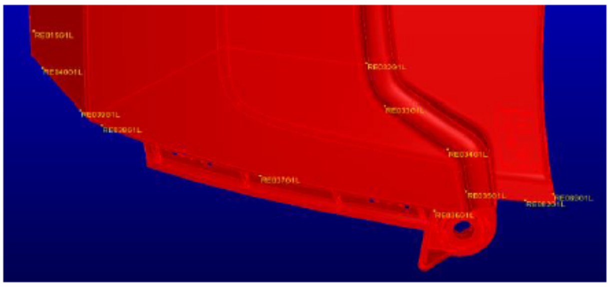
XC90 Rear Lamp - Gap

Number	Name
1	LC005G1L
2	LC090G1L
3	RE007G1L
4	RE008G1L
5	RE009G1L
6	RE010G1L
7	RE011G1L
8	RE012G1L
9	RE013G1L
10	RE014G1L
11	RE015G1L
12	RE025G1L
13	RE026G1L
14	RE027G1L
15	RE028G1L
16	RE029G1L
17	RE030G1L
18	RE031G1L
19	RE032G1L
20	RE033G1L
21	RE034G1L
22	RE035G1L
23	RE036G1L
24	RE037G1L
25	RE038G1L
26	RE039G1L
27	RE040G1L
28	RE065G2L
29	RE065G3L
30	RE066G2L
31	RE067G2L
32	RE069G1L
33	RE070G1L
34	RE082G1L









Appendix 5: Comparison of small and large samples

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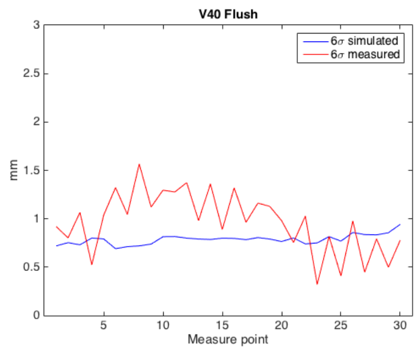
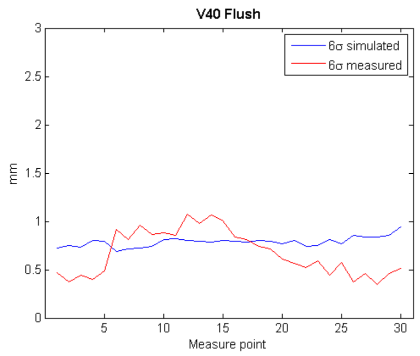
<tr><td>
</td><td>
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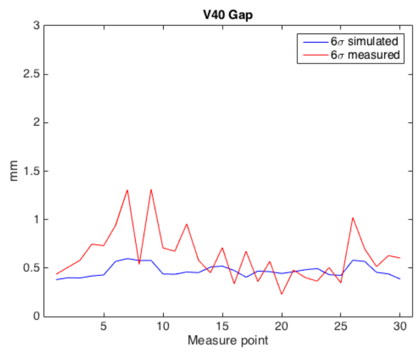
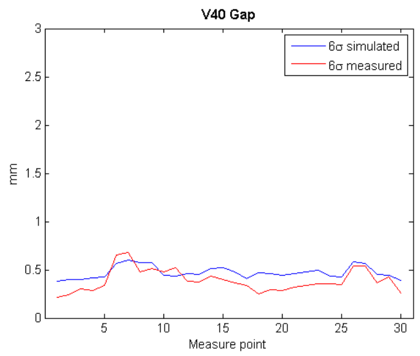
<tr><td>
</td><td>
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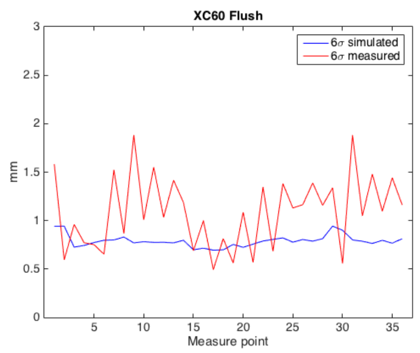
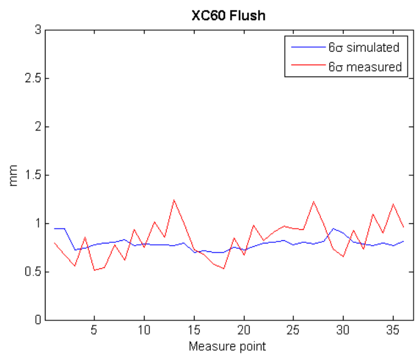
<tr><td>
</td><td>
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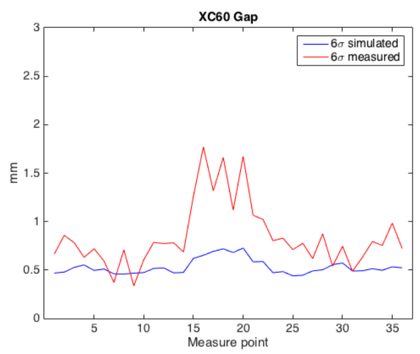
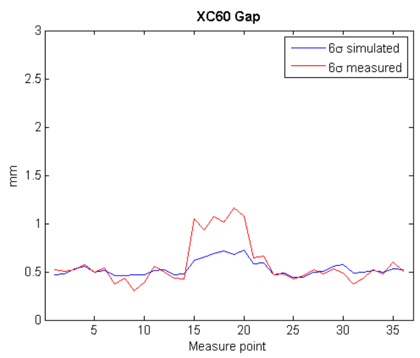
<tr><td>
</td><td>
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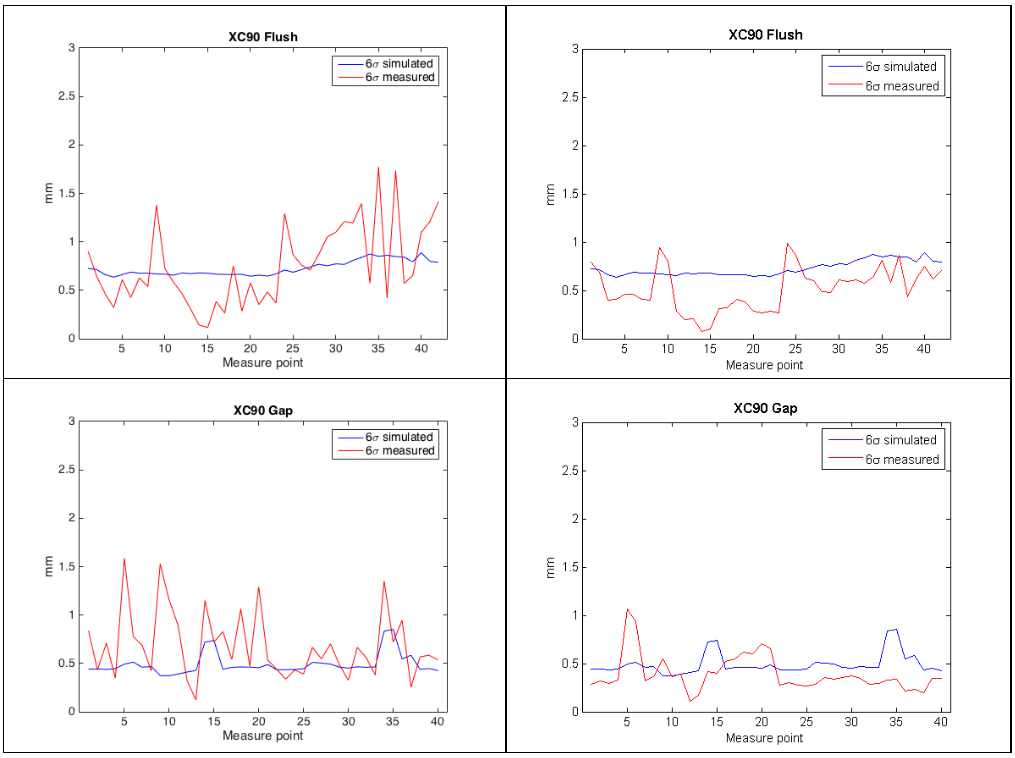
XC90 Flush
6σ simulated
6σ measured
mm
Measure point
XC90 Flush
6σ simulated
6σ measured
mm
Measure point
XC90 Gap
6σ simulated
6σ measured
mm
Measure point
XC90 Gap
6σ simulated
6σ measured
mm
Measure point

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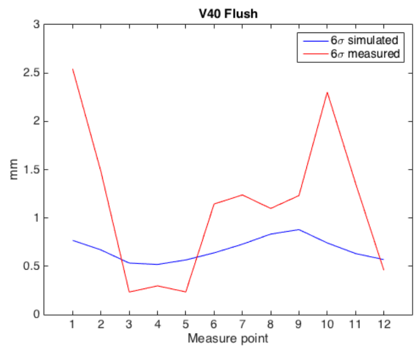
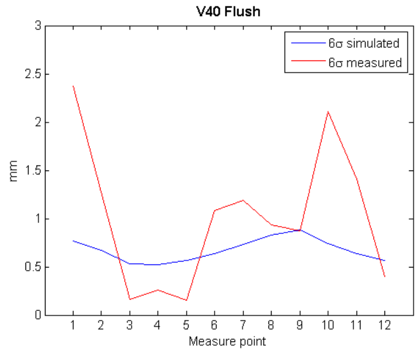
<tr><th>Small sample</th><th>Large sample</th></tr>
<tr><td>
</td><td>
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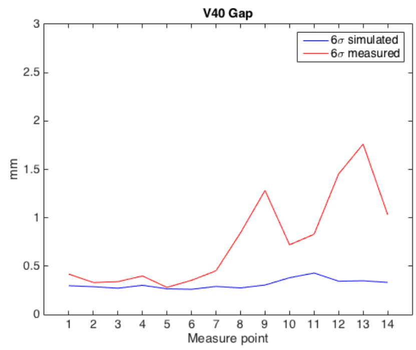
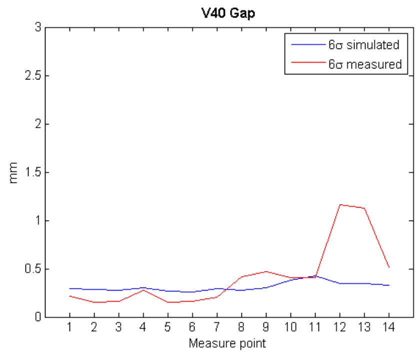
<tr><td>
</td><td>
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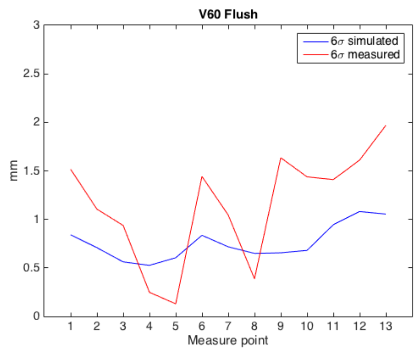
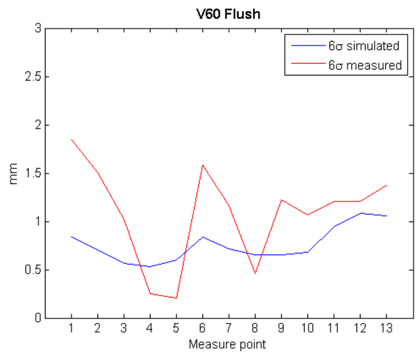
<tr><td>
</td><td>
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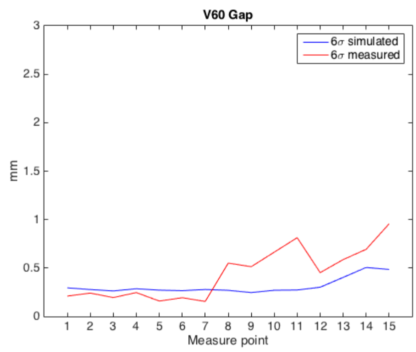
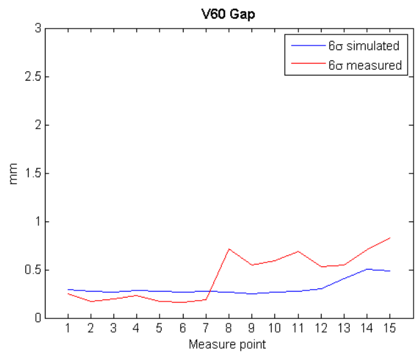
<tr><td>
</td><td>
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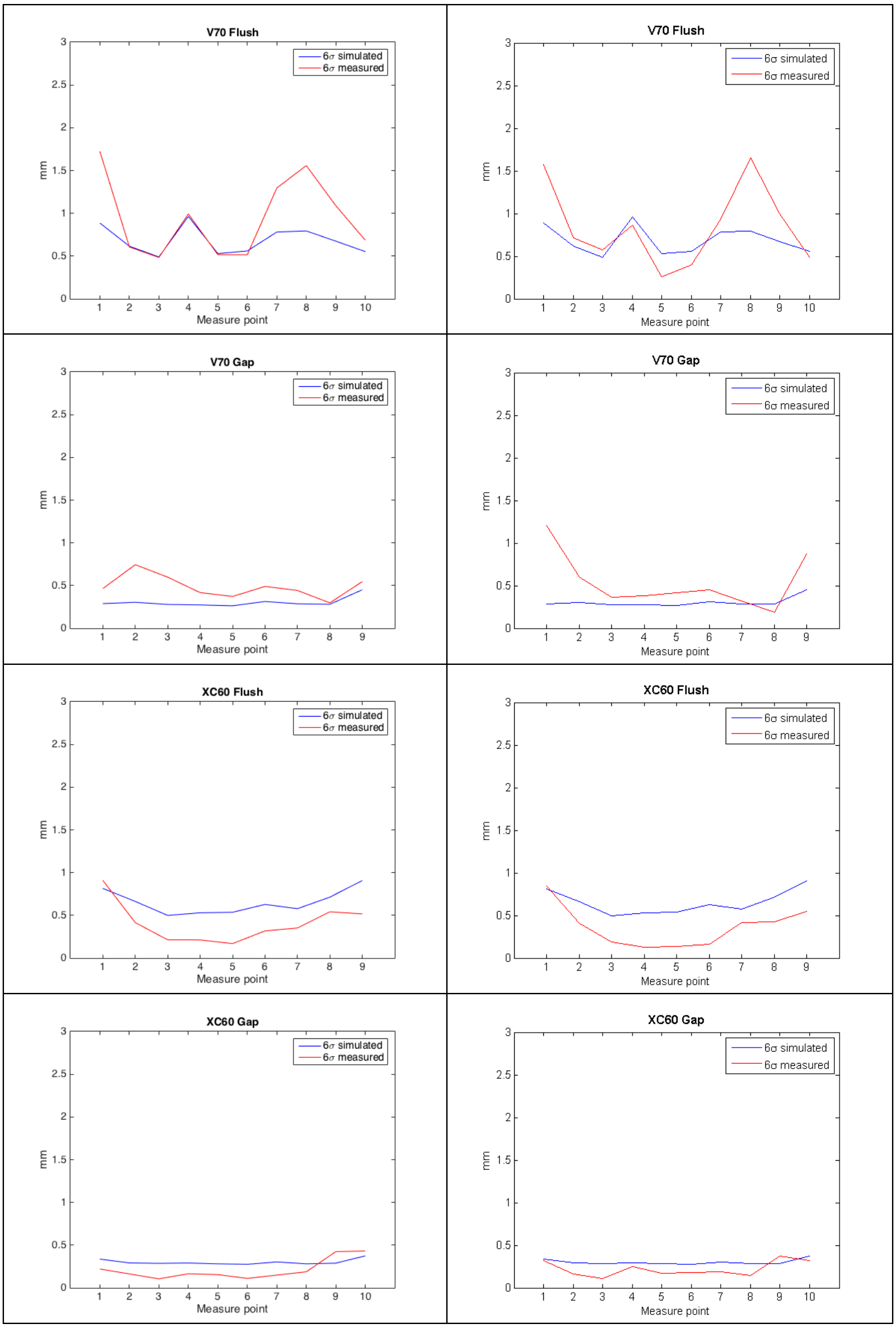
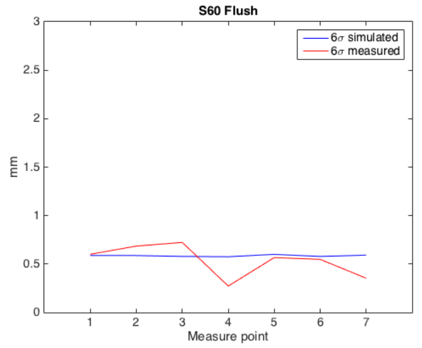
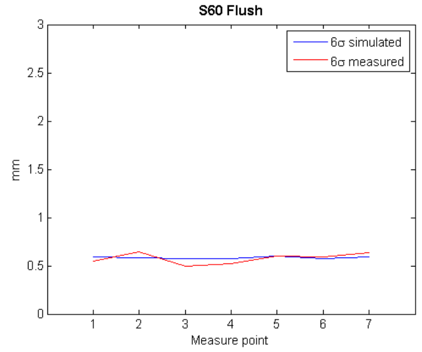
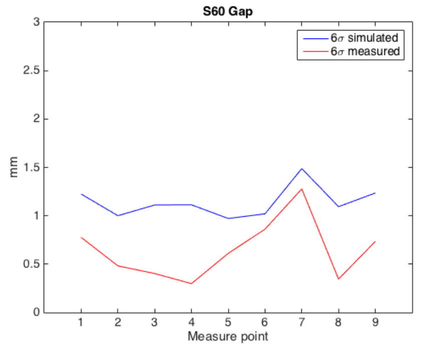
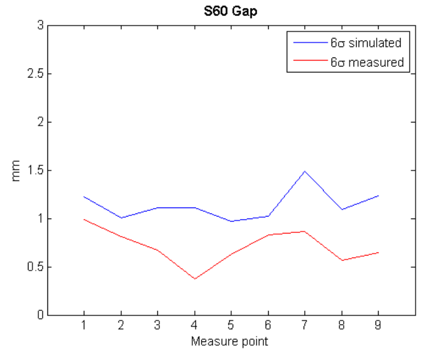

V70 Flush
6σ simulated
6σ measured
mm
Measure point
V70 Flush
6σ simulated
6σ measured
mm
Measure point
V70 Gap
6σ simulated
6σ measured
mm
Measure point
V70 Gap
6σ simulated
6σ measured
mm
Measure point
XC60 Flush
6σ simulated
6σ measured
mm
Measure point
XC60 Flush
6σ simulated
6σ measured
mm
Measure point
XC60 Gap
6σ simulated
6σ measured
mm
Measure point
XC60 Gap
6σ simulated
6σ measured
mm
Measure point

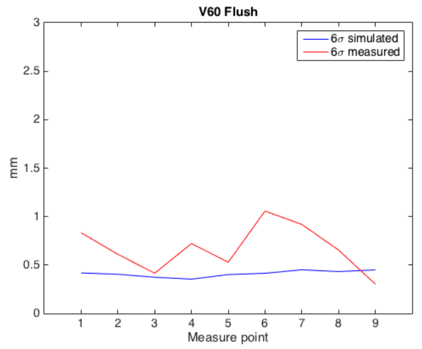
Rear lamp	
Small sample	Large sample

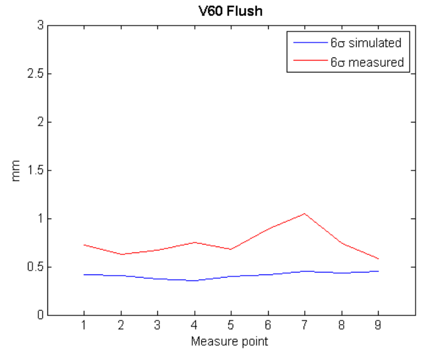


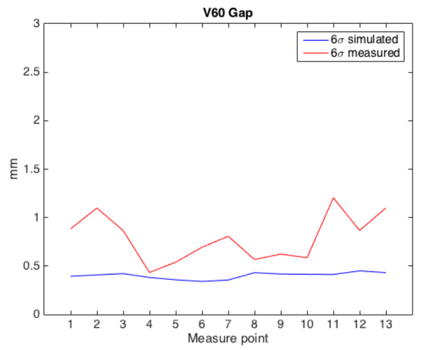


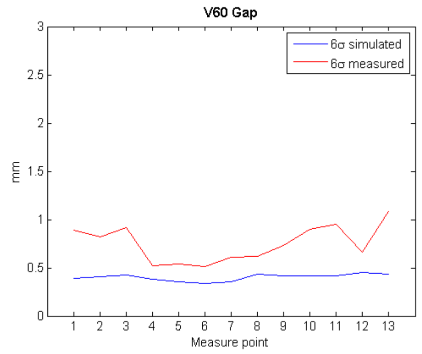


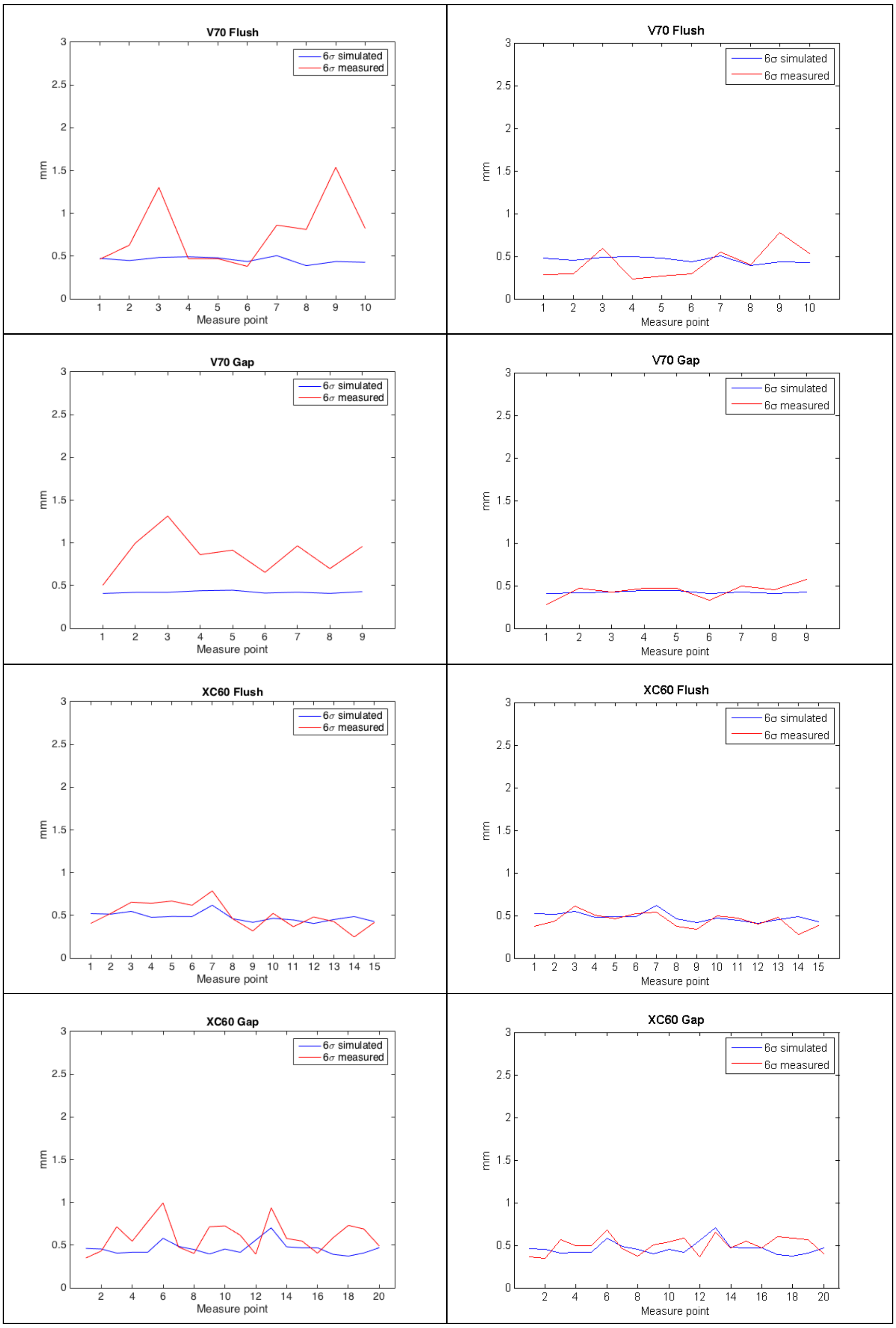






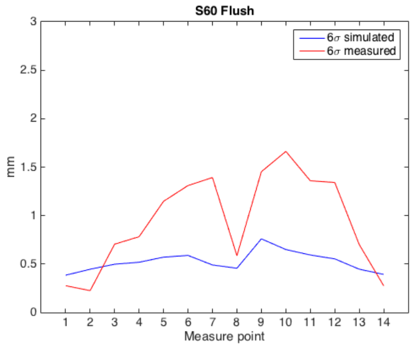


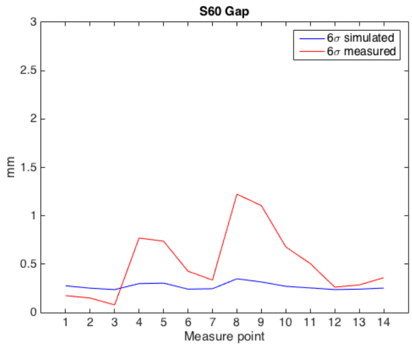


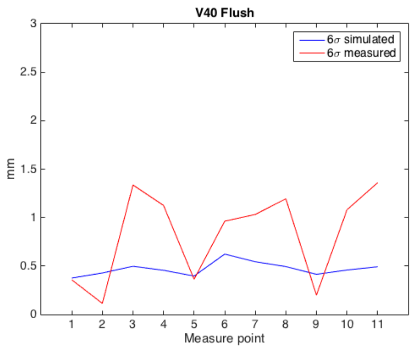

V70 Flush
6σ simulated
6σ measured
mm
Measure point
V70 Flush
6σ simulated
6σ measured
mm
Measure point
V70 Gap
6σ simulated
6σ measured
mm
Measure point
V70 Gap
6σ simulated
6σ measured
mm
Measure point
XC60 Flush
6σ simulated
6σ measured
mm
Measure point
XC60 Flush
6σ simulated
6σ measured
mm
Measure point
XC60 Gap
6σ simulated
6σ measured
mm
Measure point
XC60 Gap
6σ simulated
6σ measured
mm
Measure point

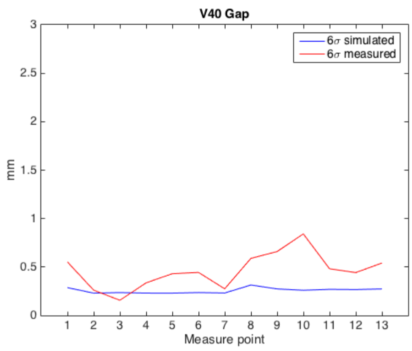
Rear door

Small sample

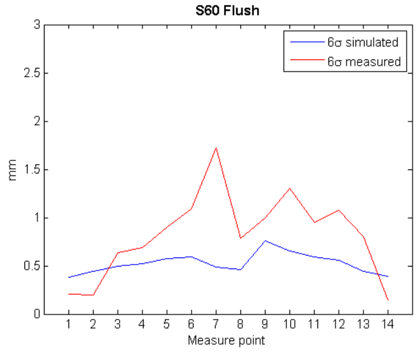


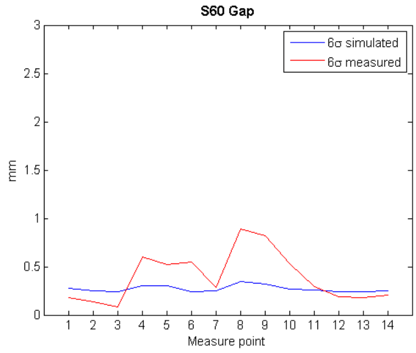


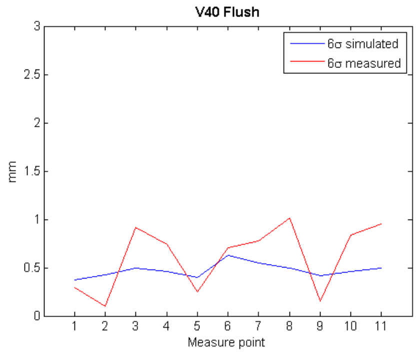


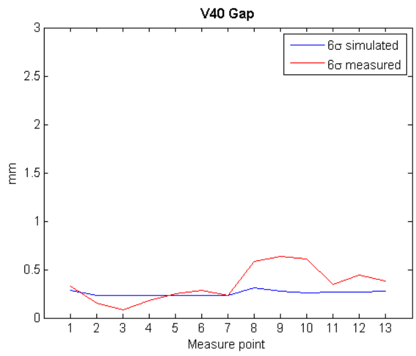


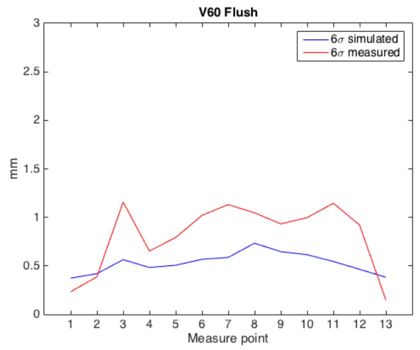
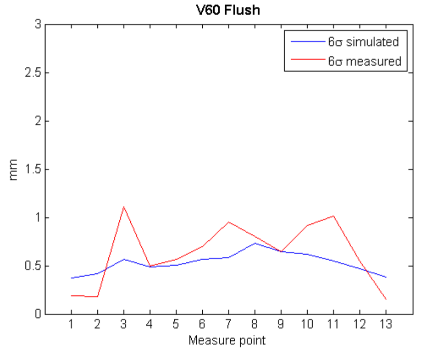
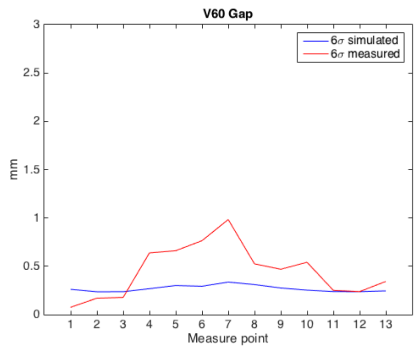
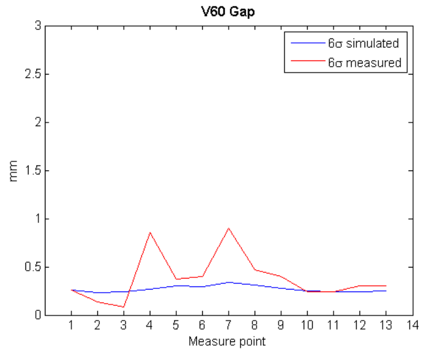
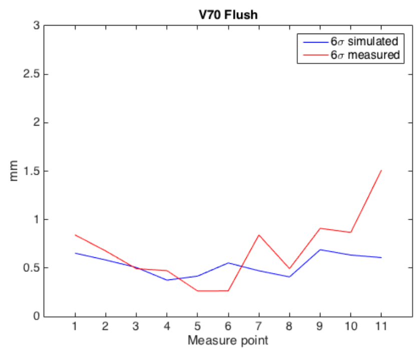
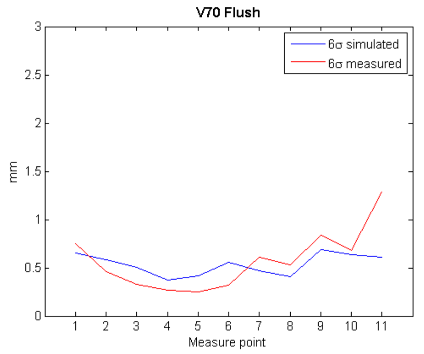
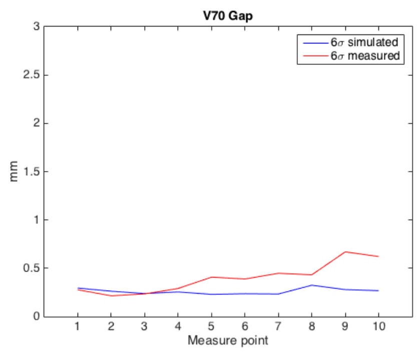
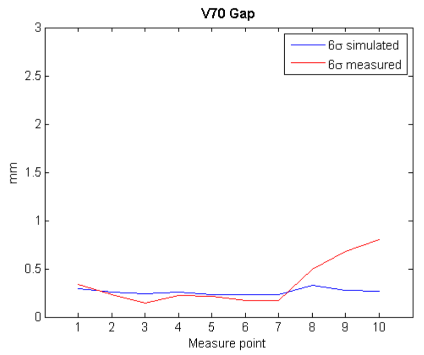
Large sample

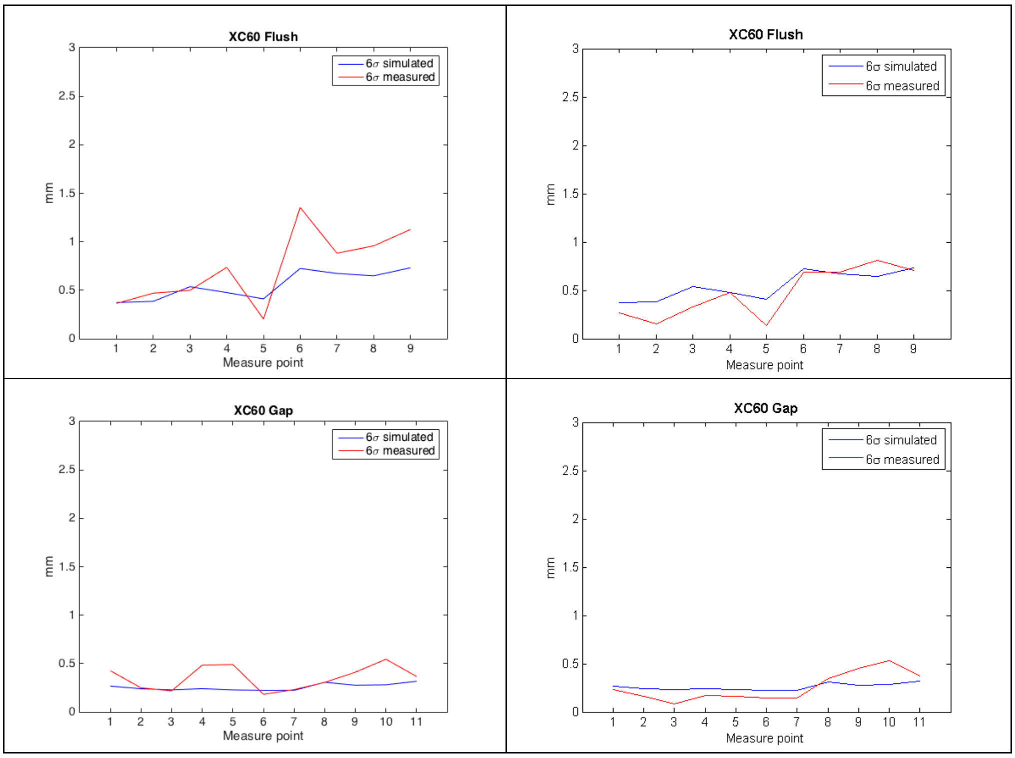






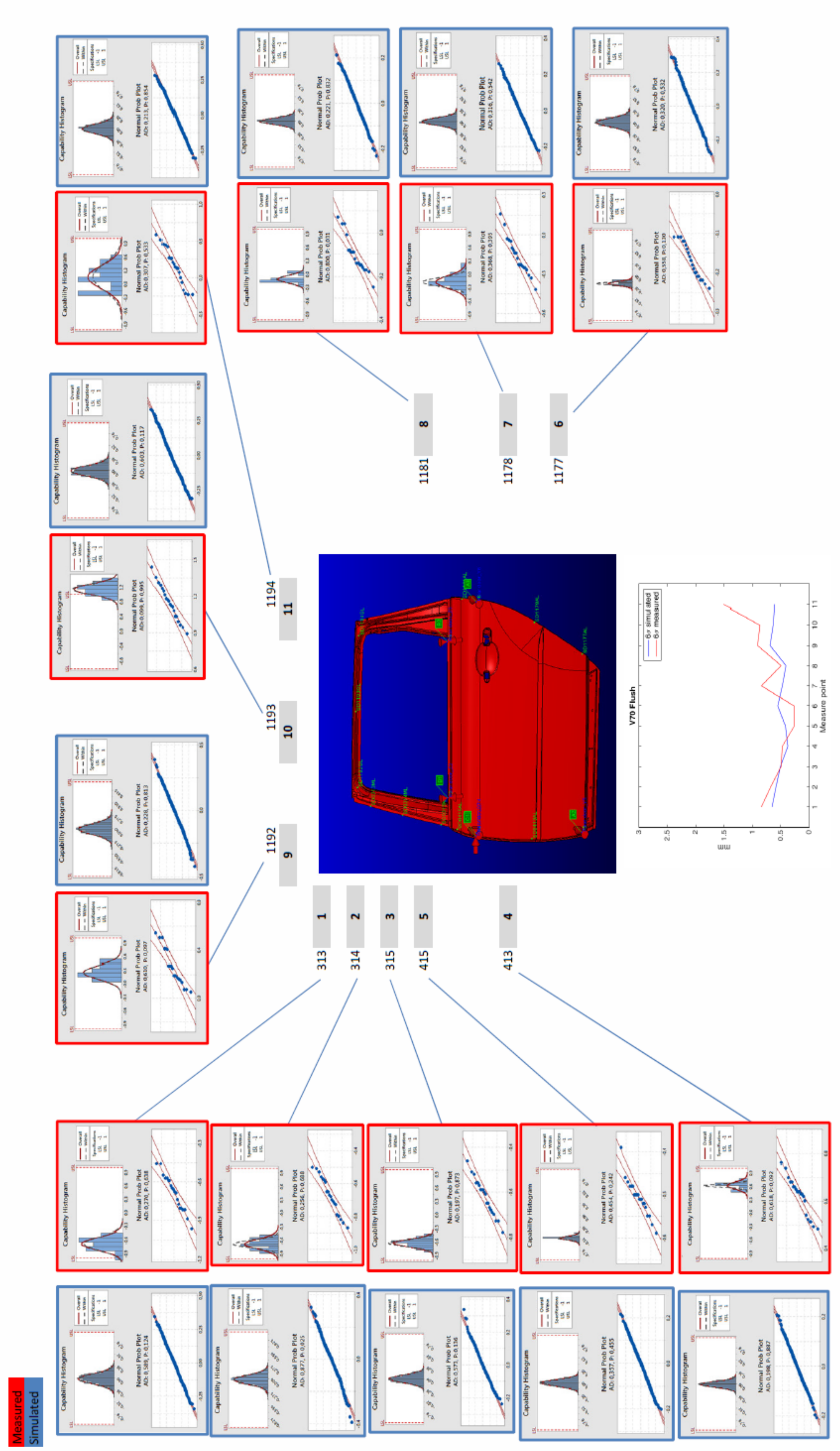



V60 Flush
6σ simulated
6σ measured
mm
Measure point

V60 Flush
6σ simulated
6σ measured
mm
Measure point

V60 Gap
6σ simulated
6σ measured
mm
Measure point

V60 Gap
6σ simulated
6σ measured
mm
Measure point

V70 Flush
6σ simulated
6σ measured
mm
Measure point

V70 Flush
6σ simulated
6σ measured
mm
Measure point

V70 Gap
6σ simulated
6σ measured
mm
Measure point

V70 Gap
6σ simulated
6σ measured
mm
Measure point


XC60 Flush
6σ simulated
6σ measured
mm
Measure point
XC60 Flush
6σ simulated
6σ measured
mm
Measure point
XC60 Gap
6σ simulated
6σ measured
mm
Measure point
XC60 Gap
6σ simulated
6σ measured
mm
Measure point

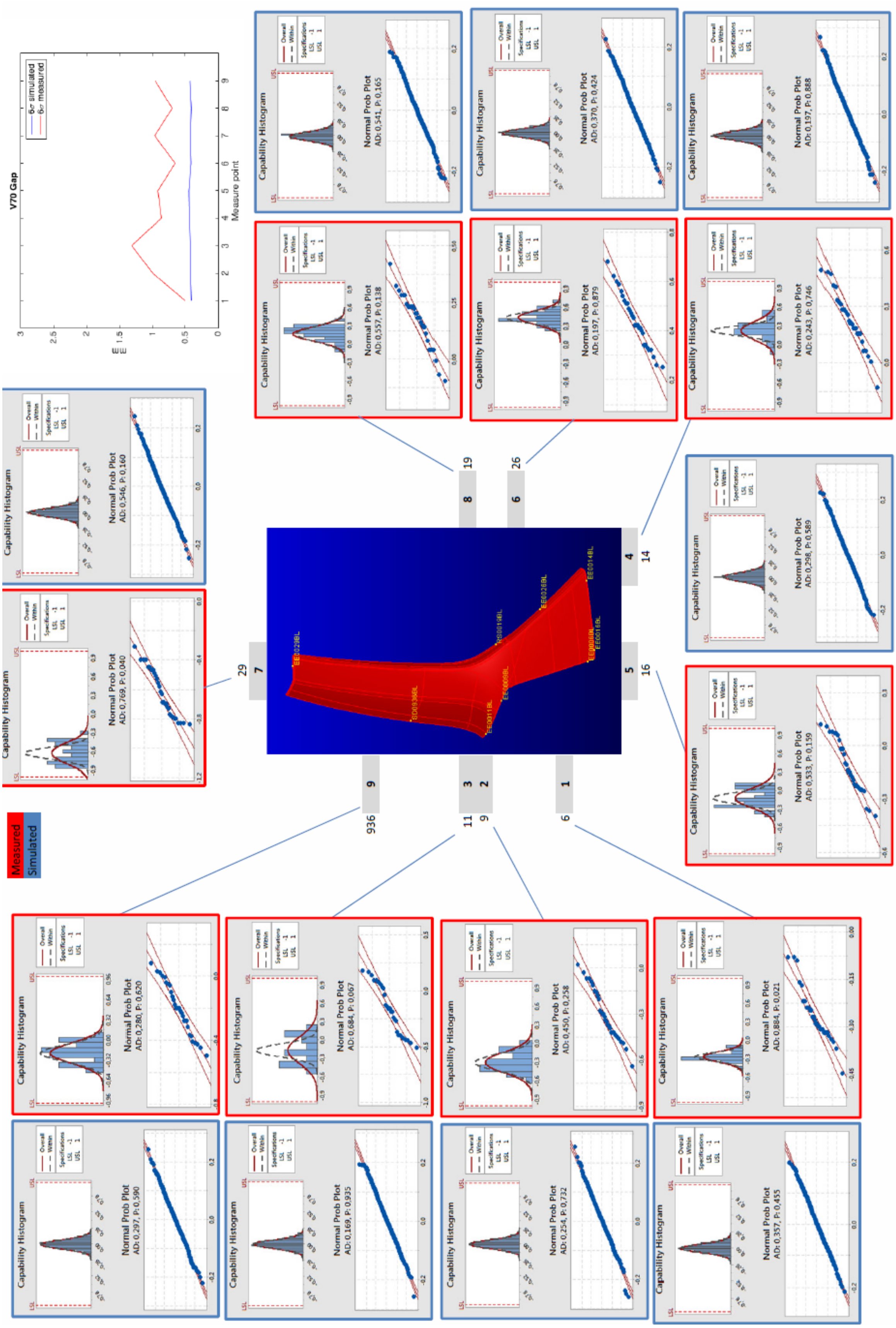
Appendix 6: Analysis of measure data

V70 Left door - Flush



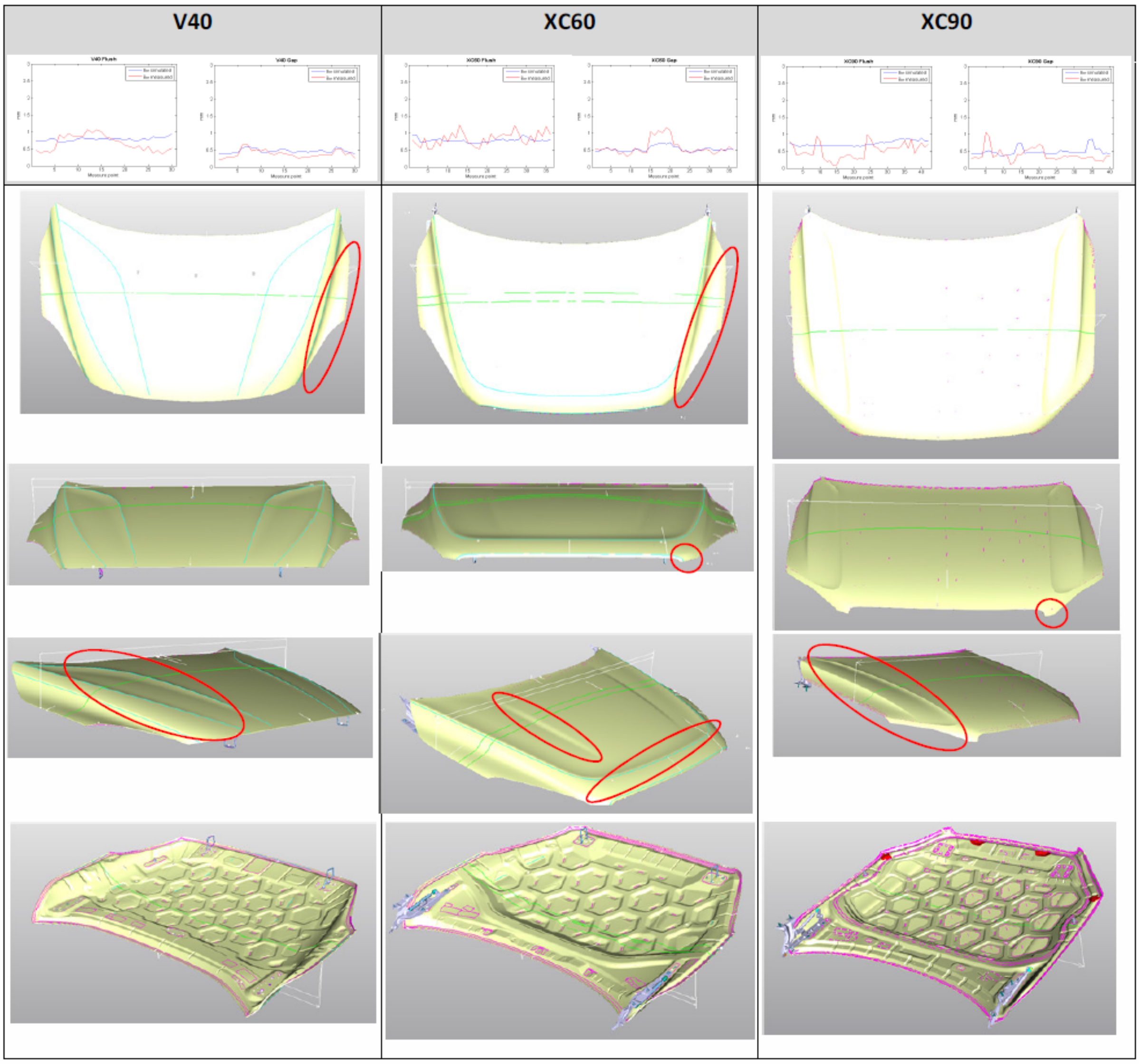
The P-value is the probability of getting a test statistic at least as extreme as the observed, given that the null hypothesis os true, i e that there are no fenomenon that needs explanation.
I e. a small P gives a large probability that the next value lies within the normal curve.
If P < 0,05, value that do not align have to be explained.

V70 Left tailgate lamp – Flush

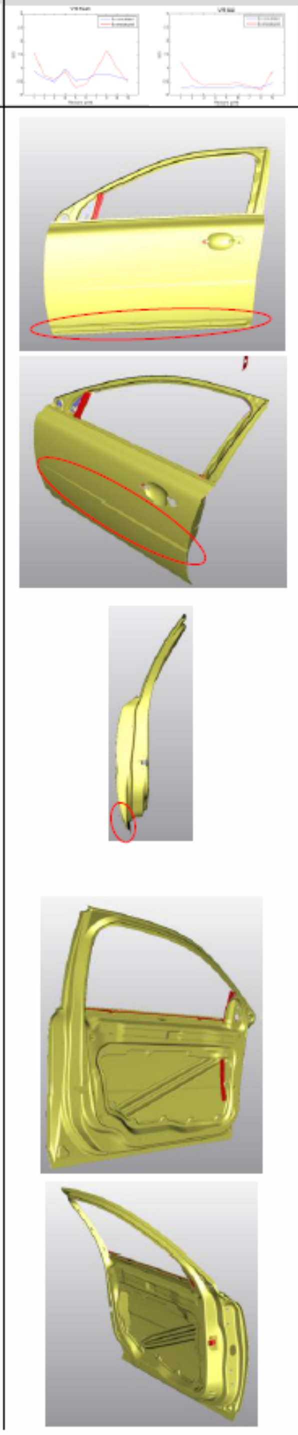
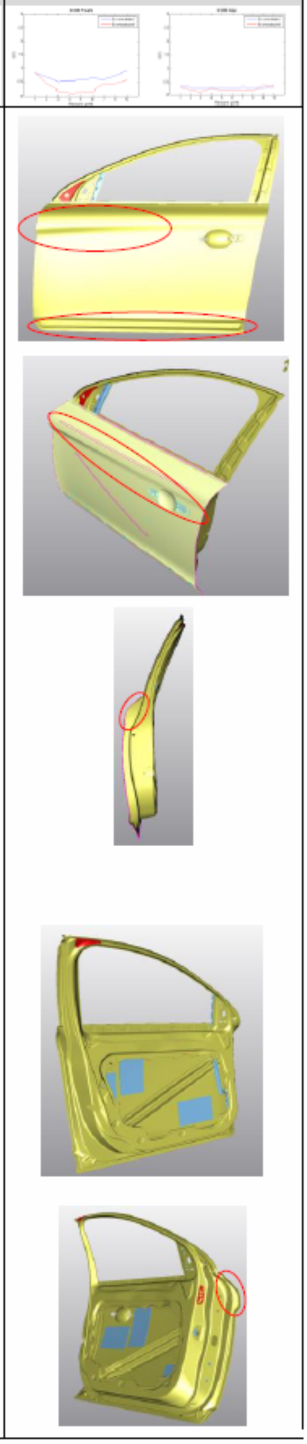


Appendix 7: Analysis of design

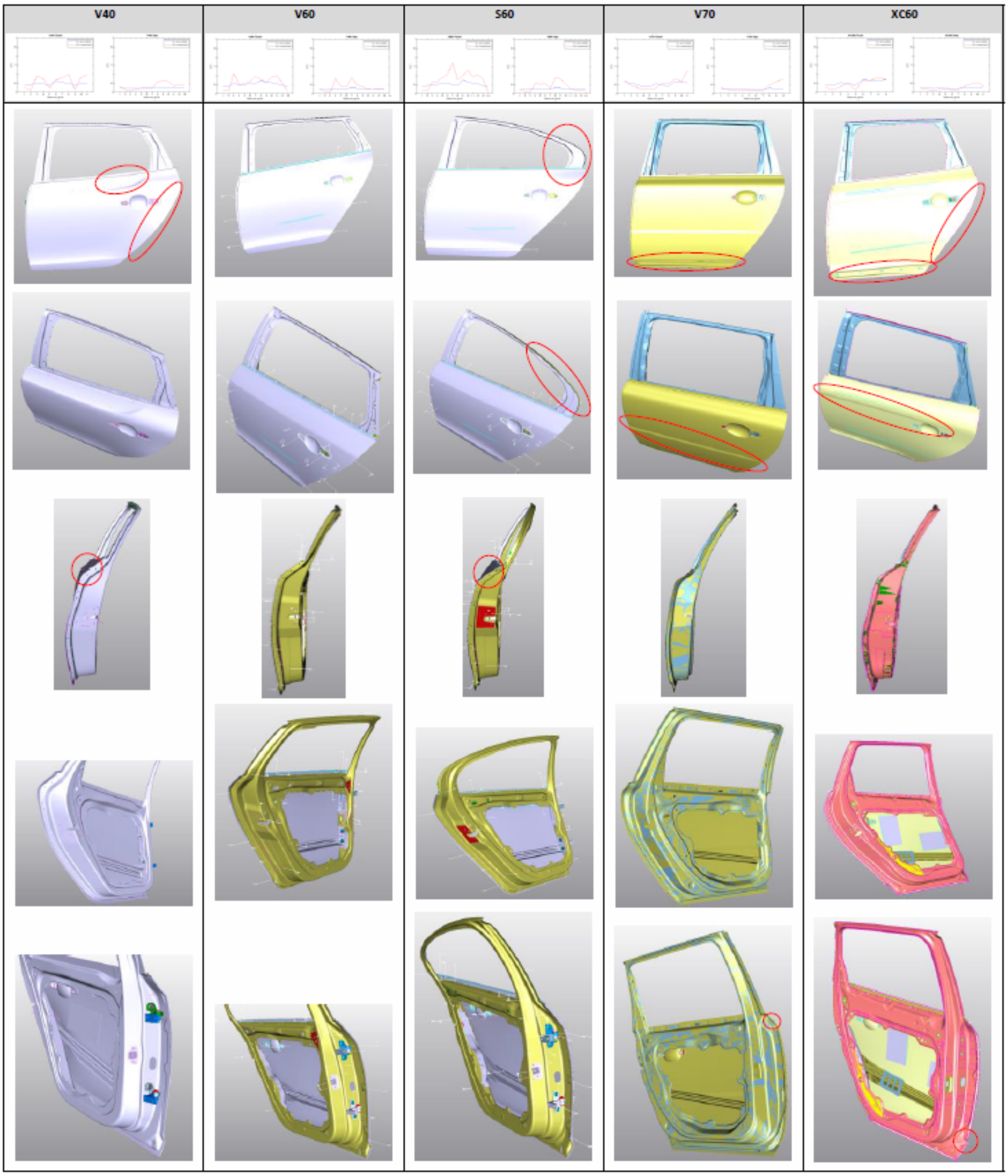
Bonnet



Front door

V40	V60 / S60	V70	XC60
			

Rear door



Appendix 8: Conclusions

Type	Conclusion	For	Against	Plausible/Rejected/Unknown	Comment
Measuring					
	The CMM machine does not give a correct view of the component and its variation. Scanning would increase the precision.	The CMM does not find the actual points but where it should have been so the variation is not entirely correct. There is a measurement error which differers along the component.	The measurement error is rather small. Investigation of the matter says that scanning and CMM yields almost the same result.	R	
Sample					
	The choice of small samples is too small.	Large samples show different results. And based on Dag's research at least 70 measures should be used. Literature says at least 20. In both cases the samples used are too small.	Even with small samples a trend is visible. For the doors it does not seem to matter which sample size is used.	P	
	The small sample measure data does not mirror the actual variation.	Minitab analyses show that the small sample data is far from normally distributed.	The small sample and the large sample give similar results for the doors.	P	
	Large sample is needed only for some components.	Doors show similar results for both small and large samples. Bonnets show much more correlation with large samples.	Using large sample on all components is not bad	P	It is not necessary, but should be used to minimize the risk for choosing an unrepresentative sample
	Window size of moving mean does not matter much.	The plot with 3, 4 and 5 measures in each window show very similar results.	Having several mean shifts could affect the best choice.	P	
	The choice of measure data is important for the end result.	The standard deviation plotted directly from the measure data (the red plot) is affected much by the choice of measure data.	The simulations and the best fit is not very dependent on the choice of measure data. The plot is only offset slightly. Not very important when using the large normalized samples.	R	For finding the correlation - not much for the simulations. Need to normalize the data before use!
	The measure data has to be treated with mean normalization before it can be used.	The large sample plots show more promising results. Large samples usually include mean shifts which is not nomally distributed. This gives large standard deviation, which does not mirror the actual variation. For the bonnets the results are much better with large samples.	For the doors the results are not affected much by the size of the sample.	P	For some components.
	One iteration of sorting out unrealistic standard deviations is enough.	The plot with 0, 1 and 2 iterations show that 1 and 2 give very similar values.		P	
Design analysis					
	Features on doors yield more promising results due to more stiffness. Therefore these can be simulated rigid, other doors should perhaps be simulated with compliancy.	Doors with features have more subdued plots. The simulated and measured curves are more aligned.	The most promising doors do not have gap/flush points in the bottom, where the other doors show most variation.	P	
	Bonnets do not show promising results. Should be simulated with compliancy.	The small sample bonnets behave unpredictable, the assumptions was that it should be simulated as rigid.	Four Z-reference points were used, should make the bonnet rigid. With larger samples the results were much better.	R	The small sample was not enough for simulating the variation the variation.
	Small triangle from the A-points amplifies the variation in RD&T and the effect of the measurement error becomes less visible.	In the calculations in RD&T this is the case. The doors have a smaller triangle and their flush is amplified more.		P	
Materials and manufacturing					
	It is hard to simulate manufacturing processes.	Measure data is hard to interpret and predict. Two similar processes do not give the same output. Most components show a very unpredictable behavior. Many noise factors are present.	There is much experience and measure data available.	P	
	Cracking is hard to simulate and affects the variation.	Flush is hard to simulate. For example the V40 flush back arch has lower variation where it i cracked, even though it is further away from locating points.	The XC90 bonnet is not cracked but still hard to simulate.	P	
	Different materials but the same component have different tolerances.	Theory suggests that different materials behave differently.	Different materials on different components has only been tested, making it hard to draw conclusions.	U	Must be tested further if implemented.
Part related tolerance					
	The generic tolerance can be used.	For some components it is promising.	But for other it is not. Should look further into measure data and normalize the mean shifts.	U	Conclusion of the whole thesis. Probably yes, but should be investigated further.
	Gap values show better results and are more likely possible to simulate.	For the most of the tested parts it seem to be the case.	Some plots are not very promising.	P	
	The found generic part related tolerances are not exact but give a hint about the size of the "final" generic tolerance.	Found generic tolerances and the measure data are in the same size. The part specific tolerance and the generic tolerance are almost the same size.	For some points the difference is large.	P	
	The exact size of the generic tolerance is not very important.	As long as it is based on the measure data it does not vary much. The curve is only offset a bit and slightly amplified. The shape of it does not change a lot.	No best fit was made after the large samples were implemented.	P	
	The generic tolerance can be applied on a completely new component.	The different general tolerances for respective component have approximately the same size and shape.	Have only tested on existing shapes.	U	